

YEAR BOOK 03/04

2003-2004

CARNEGIE INSTITUTION OF WASHINGTON

New Horizons for Science

YEAR BOOK 03/04

2003-2004

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On the cover: **Above:** Cells from the left and right sides of a zebrafish brain have different patterns of gene expression, shown by red and green.

Below: The new building for the Department of Global Ecology was designed to be energy efficient and environmentally sustainable. It was completed in March 2004.

CARNEGIE INSTITUTION
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Year Book 03/04

THE PRESIDENT'S REPORT

July 1, 2003 — June 30, 2004



ABOUT CARNEGIE

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"THE SCIENTIFIC ACHIEVEMENTS OF OUR STAFF BELIE OUR SMALL SIZE. AS A RESULT, ALL THOSE WHO ARE ASSOCIATED WITH THE INSTITUTION SHOULD BE JUSTIFIABLY PROUD OF ALL THAT HAS BEEN ACCOMPLISHED. AND WE CLEARLY CAN LOOK FORWARD TO A CONTINUING FLOW OF STUNNING SCIENTIFIC ADVANCES IN THE YEARS AHEAD."

—Richard A. Meserve



We were confronted this year with many profound transitions as a result of the deaths of several individuals whose lives were deeply entwined with the institution. Philip Abelson began his association with Carnegie as a young staff member in 1939, served as president from 1971 to 1978, and was an active member of our board of trustees until his death. Phil had many scientific accomplishments—he was the co-discoverer of neptunium, the co-inventor of a uranium isotope separation process that was crucial in World War II, the leader of an active group that undertook pioneering research in biophysics, and an investigator who conducted and directed research in geochemistry, geophysics, and experimental petrology. He was a gifted observer of scientific developments as the editor of *Science* magazine and a wise advisor to the institution. He was a truly remarkable man.

David Greenewalt, another remarkable person, also died. David was a geophysicist with a long career at the Naval Research Laboratory in Washington, D.C. He served as secretary of our board and was a benefactor of the institution. He enjoyed visiting the Carnegie departments and built a strong relationship with Carnegie staff. And several longtime staff members—Horace Babcock, Joe Boyd, Lou Brown, and Hat Yoder—also passed away this year. Each achieved many important scientific accomplishments and each helped to shape the institution in important ways. All of these individuals will be deeply missed.

Research Highlights

The directors of the six Carnegie science departments and I participated in a several-day retreat in October to discuss the future direction of the institution. To launch the session, I proposed that we have a brief discussion in which each director described the aspirations for his or her department. The discussion became so animated and interesting that it consumed most of a day. And as I think back on the event, I am struck by the range and depth of the work that is under way. The Carnegie Institution is a vibrant place with a wealth of past accomplishments and with similar grand promise for the future.

The scientific ferment that courses through every department can be illustrated with some examples of our current work. We are in a particularly exciting period at the Department of Embryology, the home of Carnegie's molecular and developmental biologists. As explained by Allan Spradling in his thoughtful essay in this Year Book, we are only at the threshold of our understanding of the deep secrets of biology. The emphasis of the department's work is quite different from that of most other biological research organizations because Carnegie scientists focus on the investigation of the difficult problems of "multicellular genomics." This discipline looks at the genetic programming of collections of cells in multicellular organisms, not just the operations within single cells. Two new staff members, Alex Bortvin and Steve Farber, have

Left: For over a hundred years, scientists at the Carnegie Institution have conducted research in the lab and in the field. Andrew Steele (below), of the Geophysical Laboratory, combines the two in Svalbard, Norway. (See page 9.)

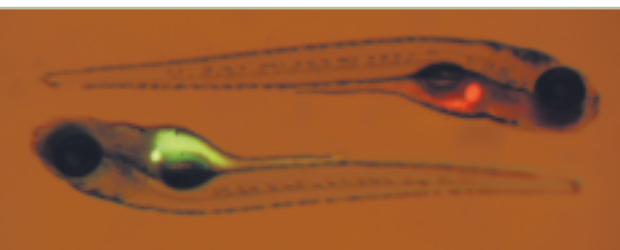


Fig. 1. Steve Farber of the Department of Embryology uses fluorescent lipids to visualize live processes in the zebrafish, *Danio rerio*, shown here. (Image courtesy Steve Farber.)

been added to the Embryology roster to strengthen this pursuit. Among other matters, Bortvin examines the role of pluripotent stem cells in embryonic development. Farber uses the zebrafish to visualize and understand biochemical processing, including that of lipids (Fig. 1). The projects of these new researchers provide a healthy complement to the exciting ongoing work by other staff. At the same time, we are preparing for the move to the handsome new Maxine F. Singer Building, which is being completed as I write this essay.

Scientists at the Geophysical Laboratory (GL) continue their pathbreaking work. The group conducting high-pressure science (led by Dave Mao and Rus Hemley) is perhaps the leading group in the world in exploring the properties of matter at pressures like those generated at the center of the Earth. This wide-ranging group has demonstrated the possibility of non-biological pathways for the formation of hydrocarbons in the Earth's deep interior. And they have developed unique techniques, using chemical vapor deposition, to produce large, single-crystal diamonds (Fig. 2) with extraordinary toughness, thereby opening possibilities for both scientific and commercial applications. At the same time, the astrobiology group, including Andrew Steele, Marilyn Fogel, and James Scott, is developing tools to enable the detection of life on other planets and in extreme environments on Earth (Fig. 3).

This year saw enormous progress at the Department of Global Ecology, including the dedication of an impressive and environmentally friendly new build-

ing (Fig. 4). Department director Chris Field continues his important work in defining the interactions among variables that affect plant growth in circumstances of elevated atmospheric carbon dioxide concentrations. Greg Asner is making great strides in the application of space- and aircraft-based remote sensing to assess ecological phenomena, including such important problems as the advancement of desertification in the American Southwest, the intrusion of exotic plants in Hawaii, and selective logging in the Amazon (Fig. 5). And Joe Berry measures the flows of carbon taken into and given up by plants over large regional areas—a necessary step in developing a global understanding of the role of the biosphere in the carbon cycle. The work of this department not only is on the cutting edge of science, but also is directly relevant to important societal issues related to climate change.

The Observatories this year benefited from the continuing outstanding performance of the Magellan telescopes—the twin 6.5-meter telescopes that Carnegie and its partners constructed at Carnegie's Las Campanas Observatory in Chile. These telescopes have provided the highest-resolution images ever achieved using a ground-based telescope without adaptive optics. Remarkable new



Fig. 2. The high-pressure team at the Geophysical Laboratory has developed a technique to produce large single-crystal diamonds extremely quickly. This brilliant-cut diamond was grown by chemical vapor deposition (CVD). It is 2.5 mm high and was made in about one day at Carnegie. (Image courtesy *Physica Status Solidi*.)

instruments have also come online,¹ promising many exciting discoveries in the years ahead. Wendy Freedman's work on the age of the universe is expanding to include the examination of dark energy and the unexpected acceleration in the universe's expansion. Pat McCarthy's study of 300 early galaxies, originally identified in the Las Campanas Infrared Survey, shows that many other scientific surprises may be on the horizon. His research has created a complex puzzle: it indicates that galaxies from the early universe were already far more mature than expected.

The Department of Plant Biology focuses on the complicated interactions that control plant development and growth, including the formation of cell walls and the transport of information and materials within a plant. This work can yield the understanding that will enable the development of crops that can grow under environmentally stressful conditions, such as drought and saline soils; that are disease-resistant; or that provide important new products (e.g., plastics). Using a novel fluorescent imaging technique, staff member Wolf Frommer monitors metabolite transport within a plant. With similar imaging methods (Fig. 7), Dave Ehrhardt is unraveling the operations of plant microtubule cytoskeletons. The genomic information underlying the department's work—indeed, for most of the world's work in plant biology—is provided by the online *Arabidopsis* database maintained by Sue Rhee.²

The Department of Terrestrial Magnetism (DTM) celebrated its 100th anniversary this year and provides, in a microcosm, an example of the evolution in the scientific endeavors of Carnegie's staff. DTM was formed to map the geomagnetic field of the Earth, but its scientific mission has changed over the years. The seismology group has devel-



Fig. 3. The Geophysical Laboratory's Andrew Steele leads the Carnegie team in the interdisciplinary international Arctic Mars Analogue Svalbard Expedition (AMASE) project. The scientists are creating a sampling and analysis strategy that could be used for future Mars missions where real-time decision making on the planet surface will be needed to search for signs of life. This outdoor lab has been set up to conduct genetic and microarray analysis in Svalbard, Norway, a geologic analogue to Mars. (Image courtesy Kjell Ove Storvik.)

oped tools to measure movements of the Earth's crust, thereby leading to a better understanding of earthquakes and volcanoes. The cosmochemistry group undertakes exquisite chemical and radiological studies of grains extracted from meteorites, leading to a better understanding of the Earth's evolution and that of our solar system. Paul Butler and his colleagues have found the majority of extrasolar planets discovered to date. Other DTM astronomers are examining the properties of these planets and the means by which they might be formed, as well as the deeper mysteries of the universe. And Sean Solomon, the department's direc-

¹ These include Eric Persson's Persson's Auxiliary Nasmyth Infrared Camera (PANIC) (Fig. 6), Alan Dressler's Inamori Magellan Areal Camera and Spectrograph (IMACS), and the Magellan Inamori Kyocera Echelle spectrograph (MIKE), developed by Steve Shectman and former Carnegie postdoc Rebecca Bernstein.

² This database, found at <http://www.arabidopsis.org/>, benefits from 5 million "hits" per month from 22,000 unique IP addresses. It is a fundamental tool for all plant biologists.



Fig. 4. The new building for the Department of Global Ecology on the Stanford campus was dedicated in April 2004. Its orientation reduces heat buildup, and temperature control is achieved naturally with a cooling tower.

tor, is the Principal Investigator on a mission that is now en route to conduct a scientific investigation of Mercury (Fig. 8).

This listing is just a small sample of the exciting work in a diverse range of fields that is ongoing in the Carnegie departments. The scientific achievements of our staff belie our small size. As a result, all those who are associated with the institution should be justifiably proud of all that has been accomplished. And we clearly can look forward to a continuing flow of stunning scientific advances in the years ahead.

The Challenge

Despite the obvious strength of our efforts, the institution confronts a challenge in maintaining its unique character. In defining the aims of the fledgling institution, Andrew Carnegie explained that the institution should “discover the exceptional man in every department of study whenever and wherever found . . . and enable him to make the work for which he seems specially designed his life work.”³ Although the mode of functioning shifted from an emphasis in the early years on grants to individual scientists to the establishment of departments staffed by Carnegie scientists, the continuing objective has been to provide exceptional scientists with the freedom to pursue their instincts as to fruitful areas of research.

Thus, consistent with Andrew Carnegie’s goal, we seek to nurture scientific advances of a particular character—we seek to enable scientists of great creativity and insight to pursue difficult questions of their own choosing. As researchers have remarked, “The institution buys our time and gives it back to us.”⁴ The work is usually conducted by individuals or small groups—big science is not our customary style, although there are important exceptions. Indeed, we try to nurture a contrarian philosophy through the pursuit of research opportunities that are not similar to activities elsewhere. We are proud of our scientists’ willingness to pursue science that is far from the mainstream because of the high risk of failure, the difficulty of the problem, or the need for extended effort to achieve results. It is unfashionable research that is likely to lead to paradigm shifts or to significant and surprising advances.

History shows that such an approach is remarkably successful. For example, Edwin Hubble, a Carnegie astronomer for almost all of his adult life, revolutionized astronomy with his discovery that the universe is expanding. Einstein remarked that his adjustment of the general theory of relativity to provide for a static universe was his “biggest blunder.”⁵ Carnegie’s Barbara McClintock pursued work that was largely unappreciated at the time on the patterns of genetic inheritance in corn, ulti-

mately winning the Nobel Prize for her work. The efforts under way in each of our departments today hold the promise of similar startling advances.

Nonetheless, there is a practical challenge arising from the fact that our dreams can exceed our financial capacity—a not unusual dilemma in human affairs. I suspect that every president has tried to chart a course that seeks to ensure the pursuit of the Carnegie vision within the limits of available funds.⁶ I confront the same challenge.

Supporting Carnegie Science

In the early years, Carnegie scientists were funded entirely from the endowment. In fact, until the late 1970s, Carnegie scientists did not customarily seek funds from the federal government. In the face of shortfalls in institutional income, President Vannevar Bush had undertaken a process of “terminations and taperings” of departments to fit the scientific program within the limits of our budget.⁷ But the funding problems continued. By the mid-1970s, the value of the endowment had decreased

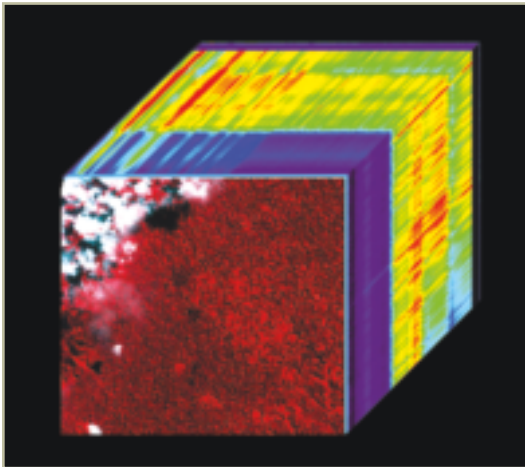


Fig. 5. This “data cube” is from the EO-1 satellite. It shows the Amazon forest canopy in the near infrared. Each pixel contains a spectral signature that the Asner group at the Department of Global Ecology analyzes for water, pigments, and other constituents. (Data courtesy NASA; processing and analysis done at Carnegie.)

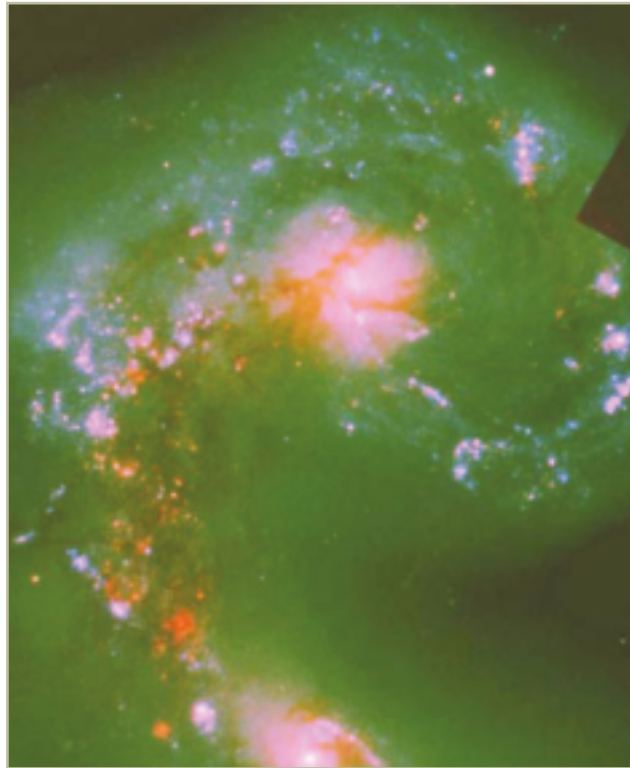


Fig. 6. PANIC is the first near-infrared camera built for the Observatories’ Magellan Project. Shown here are the pair of interacting galaxies called the Antennae, among the first objects imaged with it. The Antennae consist of many young, massive star clusters and a great deal of dust. Very dusty regions are much easier to see in the near infrared, and PANIC is able to peer into these areas with great clarity. This picture is a composite of Hubble Space Telescope and PANIC data. (Image courtesy Eric Persson.)

³ Andrew Carnegie, Deed of Trust, 1902, Year Book no. 1 (Washington, D.C.: Carnegie Institution of Washington, 1903).

⁴ J. Trefil and M. Hazen, *Good Seeing* (Washington, D.C.: Joseph Henry Press, 2002).

⁵ G. Gamow, *My World Line* (New York: Viking Press, 1970).

⁶ M. Singer, “The President’s Commentary,” Year Book 99/00 (Washington, D.C.: Carnegie Institution of Washington, 2001).

⁷ V. Bush, “Report of the President,” Year Book no. 38 (Washington, D.C.: Carnegie Institution of Washington, 1939).

at a time when the demands for funds were growing. As a result, in the late 1970s, President Philip Abelson proposed to move “with caution” in accepting federal funds.⁸

Abelson was concerned about this move because of the danger that it would change the fundamental character of the institution. He feared there would be a temptation to pursue fashionable work and thereby enhance the likelihood of funding success. Pressures might arise to pursue short-term projects so that scientific success could be demonstrated rapidly, thus making a continuing flow of federal funds more secure. He feared that scientists would devote too much of their time to preparing applications for grants and reporting to grant agencies on their work, rather than pursuing science. And the attachment of scientists to the institution might diminish if their livelihood resulted from federal support. Indeed, it was feared that Carnegie’s success in recruiting exceptional scientists might diminish if the freedom we allowed our researchers were constrained. As a result, President Abelson suggested various limitations on federal support to

avoid these hazards, such as the rule that no part of staff salaries should come from grants.

As time has gone on, the various limitations on federal support have fallen aside. In the face of a growing need to finance science and the constraints on spending that could be covered by the endowment, the principal means to meet any shortfall has been to pursue federal money. As a result, and as shown by Figure 9, the operating budget derived from federal support has grown over the years.⁹ In a certain sense, the continuing success of the institution’s scientists in obtaining grants is a testament to the quality of our staff.

Nonetheless, reliance on federal support is at least theoretically worrisome. We should have concern that the potential hazards that troubled Abelson might become realities. Chief among these is the fear that the pressure to obtain federal grants could become so great that the character of the science the institution seeks to pursue might fundamentally change and the uniqueness to which the institution aspires might disappear. We could simply become yet another of the multitude of universities and other scientific enterprises undertaking activities largely defined by the availability of federal funding.

This worry is compounded by the fact that there is no immediate feedback mechanism to constrain the pursuit of federal support. In fact, because federal support, where available, serves to liberate endowment funds for other things, there is a value to the institution and to each scientist’s colleagues in pursuing a grant. The hypothetical danger is that, by a process of accretion, the institution could become so dependent on federal funds that our scientists might feel excessive pressure to tailor their activities to achieve funding success.

I have undertaken extensive discussion with the directors about this matter and am assured that this hypothetical danger is not yet real. They are sensitive to the issue and are prepared to intervene as necessary. Moreover, we undertake periodic examinations of each of our departments by visiting committees made up of trustees and outside

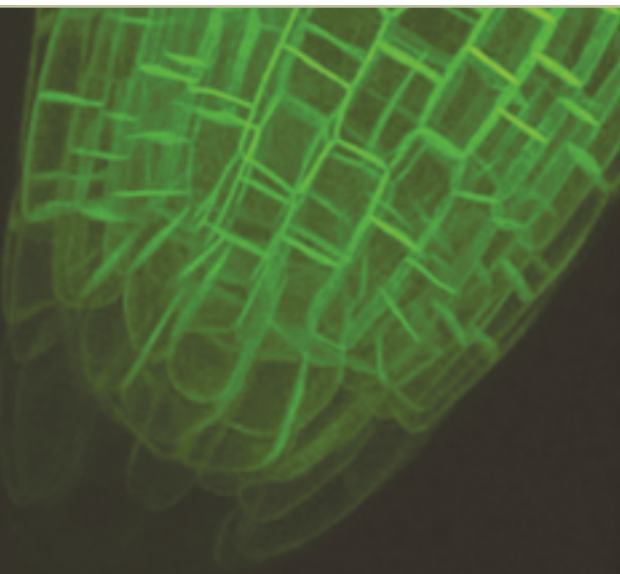


Fig. 7. Dave Ehrhardt of the Department of Plant Biology produced this three-dimensional reconstruction of a plant root tip by stacking layers of confocal microscopic images. The plant is making a fluorescently tagged protein that outlines the cell surface. (Image courtesy David Ehrhardt.)



Fig. 8. Department of Terrestrial Magnetism director Sean Solomon is Principal Investigator for the MESSENGER mission to Mercury. He stands in front of the packaged MESSENGER craft at the Goddard Space Flight Center, where it underwent testing before leaving for Cape Canaveral in March 2004.



experts in relevant scientific fields, and I have charged (and will continue to charge) each of the visiting committees to evaluate whether the performance of each department comports with the Carnegie vision. The reports received to date are very reassuring in this (and other) respects. Although it might be better to have a self-regulating feedback mechanism that serves to limit federal support, I am confident that the character of the institution's science has not been compromised as a result of the changing funding patterns.

Moreover, the harsh reality is that any concern about excessive federal support may soon seem a problem from a distant and happy time. As a result of fiscal pressures, there are likely to be very significant cuts in the discretionary parts of the budget for the indefinite future. Support for basic research across the government in the FY 2005 budget does

not stay even with inflation and some agencies, such as the National Science Foundation, confront cuts of over \$100 million. The National Institutes of Health, which has grown accustomed in recent years to substantial increases in funding, instead faces only a minor increase of 2%. And, although Congress is just starting to review the FY 2006 federal budget, it appears we will confront another lean year for science. As a result, the competition for federal funds can be expected to grow. Although the special capabilities of Carnegie scientists may result in continuing and even growing success in pursuit of federal funds, it would be reckless to anticipate such an outcome.

Other Funding Options

This situation, then, presents a dilemma. Science has grown ever more costly, largely because the laboratory equipment necessary to pursue issues at the cutting edge has grown ever more precise, sophisticated, and thus expensive. We cannot anticipate growth in federal support. How then are we to pay our way?

Careful tending of the endowment is an obvious strategy—and one that we have followed scrupulously. We have had the benefit of an extraordinary finance committee, chaired by David Swensen, chief investment officer of Yale University. As a result of the work by David and his colleagues, our endowment over the past decade has achieved a net return of 12.2% annualized, which is significantly greater than the 9.8% achieved by the typical endowment (as reported by the State Street Endowments and Foundations Universe benchmark). We follow a spending rule—roughly 5% of the three-year average value of the endowment at fiscal year end—to seek to ensure support for

⁸ Carnegie Institution of Washington, *Minutes of the Special Meeting of the Board of Trustees, Seventy-Ninth Meeting*, Washington D.C., March 18, 1977.

⁹ The growth in federal funding may not be completely revealing because some of the federal funds are for a few large projects, such as MESSENGER and TAIR, in which a substantial portion of the funds in fact flow through Carnegie to others.

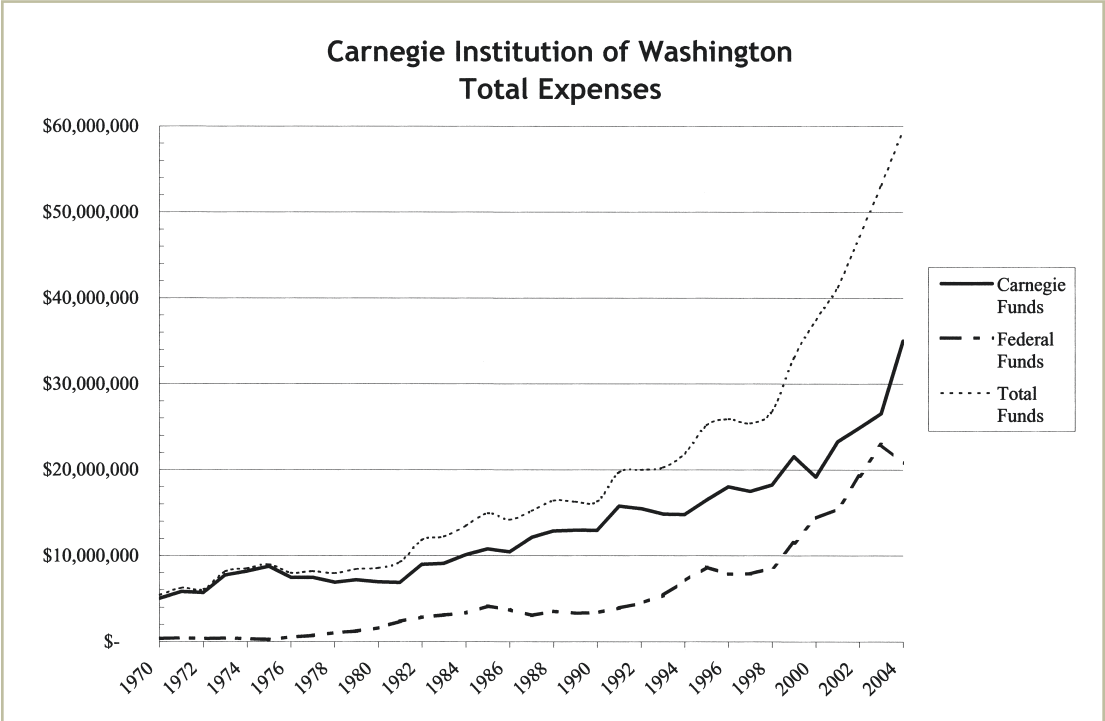


Fig. 9. Total expenses are indicated by this graph. The numbers are actual dollars and are not normalized for inflation. Expenditures represent the sum of operating and equipment expenses; capital outlays are not included. For some years, the total funds expended is larger than the sum of Carnegie and federal funds because of private grants. Prior to 1999, some funds included in the private fund category were actual federal funds provided through subcontract with partners at other research institutions.

present needs while preserving the value of the endowment for the future. Because of the skill of our finance committee, our endowment has grown significantly in real terms. But our investment strategy can lead only to incremental, albeit important, increases in spending at a time when the real costs of science are growing rapidly.

Another possible source of funds is royalties from the intellectual property arising from our scientists' work. We follow this strategy as well. Carnegie pursues patents in appropriate cases, resulting in a steady flow of funds.¹⁰ But, as a general matter, universities that have sought to maximize the return from intellectual property have not obtained

significant gains—the technology transfer offices at universities typically cost more than they earn—although there have been a few “home runs.”¹¹ The results of basic research typically lead to commercial applications only after extensive further applied research and development—indeed, the exact nature of the commercial applications may not even be knowable at the time the basic research is performed—and thus the development of commercial applications is fundamentally different from the pursuit of basic science. Although the institution should and will continue to pursue commercial gains from our intellectual property where possible, if we are to remain true to our mission, we must avoid the distortion of our work that would arise from a focus on commercial applications. It thus should not be anticipated that our intellectual property will provide a means to address to our funding dilemma.

An alternative strategy is to pursue the process of “terminations and taperings” undertaken by President Vannevar Bush and to cut activities back to a level that our finances can support. But this is not an attractive strategy in light of the remarkable level of scientific productivity that is found in each of the Carnegie departments. The board and I are committed to maintaining a strong institution across all departments.

This leads to the final and most important source of support: the pursuit of grants and donations from private foundations and individuals. Carnegie has benefited over the years from the generosity of foundations and individuals, particularly our own trustees. But we do face a special challenge in this

respect. Some grant makers and donors understandably look at the large support of science by the federal government and conclude that the opportunity to have an impact may be greater in other philanthropic areas. The Carnegie philosophy—the pursuit of unique science—should serve to overcome this barrier to some extent. But there is also the reality that the impact of basic science is very uncertain, although in the aggregate, basic science will no doubt be the fundamental force that will change our lives and those of our children for the better. For example, the work of our scientists in the Department of Embryology will provide the insights that allow medical miracles to occur, but we cannot promise that this work will lead directly to the cure of any particular disease. We thus must seek donors with the special insight of Andrew Carnegie when he initially endowed the institution. His words, when presenting his trust deed to the board of trustees in 1902, reveal his remarkable understanding of the power of discovery: “...your aims are high, you seek to expand known forces, to discover and utilize unknown forces for the benefit of man. Than this there can scarcely be a greater work.” This underlying belief in the value of discovery has led to a century of scientific successes and will continue to remain a guiding force of the institution. I am confident that we will find supporters with this unique understanding in the years ahead.

—Richard A. Meserve

¹⁰The royalties are shared among the scientists responsible for the patented invention, the department in which those scientists work, and the institution.

¹¹J. G. Thursby and M. C. Thursby, “University Licensing and the Bayh-Dole Act,” *Science* 301, p. 1052, August 22, 2003.

GAINS

John Chambers joined the Department of Terrestrial Magnetism as a staff member in April 2004.

On August 1, 2003, **Burkhard Militzer** joined the Geophysical Laboratory as a staff associate.

Alex Schreiber was appointed staff associate at Embryology during 2003.

TRANSITIONS

Trustee **Deborah Rose** was elected secretary to the Carnegie board of trustees in May 2004. Trustee **Burton McMurtry** was elected a senior trustee at the same time.

David Ehrhardt, formerly a staff associate at Plant Biology, became a staff member on July 1, 2003.

Longtime Embryology staff member **Andrew Fire** joined the Stanford University School of Medicine as professor in the Department of Pathology in November 2003.

Geophysical Laboratory research scientist **Viktor Struzhkin** was appointed to staff member on July 1, 2003.

HONORS

Embryology

Director **Allan Spradling** won the Edwin Grant Conklin Medal of the Society for Developmental Biology in August 2003.

Geophysical Laboratory

Marilyn Fogel was elected a fellow of the Geological Society of America.

Robert Hazen was elected vice president of the Mineralogical Society of America.

Former department director **Charles Prewitt** was awarded the 2003 Roebling Medal of the Mineralogical Society of America in November 2003.

Plant Biology

Staff member **Wolf Frommer** was elected a fellow of the AAAS.

Director **Chris Somerville** was the Sir Frederick Gowland Hopkins Memorial Lecturer for 2004. The award is bestowed by the Biochemical Society.



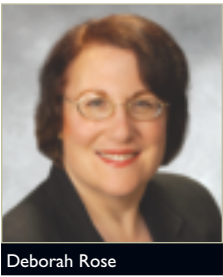
John Chambers



Alex Schreiber



Burkhard Militzer



Deborah Rose



Burton McMurtry



Viktor Struzhkin



David Ehrhardt

Terrestrial Magnetism

Staff member **Paul Butler** was one of five winners of the 2003 *Discover* Magazine Award for Innovation in Science and Technology. He received the award for his work on extrasolar planets. He also delivered the Carl Sagan Lecture at the fall 2003 meeting of the American Geophysical Union.



Philip Abelson

Staff members **Richard Carlson** and **David James** became fellows of the American Geophysical Union. James was also selected as an IRIS/Seismological Society of America Distinguished Lecturer for 2003-2004.

Senior Fellow **Vera Rubin** received the James Craig Watson Medal and prize in April 2004 from the National Academy of Sciences.



Francis (Joe) Boyd

Director **Sean Solomon** delivered the annual A. O. C. Nier Memorial Lecture in October 2003.

Director emeritus **George Wetherill** was awarded the Henry Russell Lectureship from the American Astronomical Society in February 2004.

DEATHS



Louis Brown

Former Carnegie president and trustee **Philip Abelson** died on August 1, 2004, at the age of 91.

Horace Babcock, former Observatories director, died on August 29, 2003, at age 90.

Francis (Joe) Boyd, staff member emeritus at the Geophysical Lab, died at age 77 on January 12, 2004.



David Greenewalt

Louis Brown, 75-year-old staff member emeritus at the Department of Terrestrial Magnetism, died on September 25, 2004.

Longtime trustee and secretary of the Carnegie board **David Greenewalt** died October 21, 2003, at age 72.

On August 2, 2003, director emeritus of the Geophysical Laboratory **Hatten S. Yoder, Jr.**, died at age 82.



Hatten S. Yoder, Jr.

Toward Tomorrow's Discoveries

The Carnegie Institution received gifts and grants from the following corporations, foundations, individuals, government agencies, and other sources during the period July 1, 2003, to June 30, 2004.

FOUNDATIONS AND CORPORATIONS

\$1 Million or More

The Deborah Rose Foundation
Sidney J. Weinberg, Jr. Foundation

\$100,000 to \$999,999

Crystal Trust
Gayden Family Foundation
Howard Hughes Medical Institute
The Fletcher Jones Foundation
Koerber Foundation
Richard Lounsbery Foundation
The G. Harold and Leila Y. Mathers Charitable Foundation
Ambrose Monell Foundation

\$10,000 to \$99,999

Abbott Laboratories Fund
Ahmanson Foundation
The Morris & Gwendolyn Cafritz Foundation
Carnegie Institution of Canada/Institution
Carnegie du Canada
Richard W. Higgins Foundation
Suzanne Nora Johnson and David G. Johnson Foundation

\$1,000 to \$9,999

The Bristol-Myers Squibb Foundation, Inc.
The Philip Stoddard Brown and Adele Smith Brown Foundation
James E. and Diane W. Burke Foundation, Inc.
EHDD Architecture
Paul and Annetta Himmelfarb Foundation
The Whitaker Foundation

INDIVIDUALS

\$1 Million or More

Caryl Haskins Estate

\$100,000 to \$999,999

Michael E. Gellert
Robert and Alexandra Goelet
David Greenewalt
Burton J. and Deedee McMurtry
Jaylee and Gilbert Mead
Grace Stephenson Trust
Thomas N. and Mary Urban

\$10,000 to \$99,999

Mr. and Mrs. G. Leonard Baker, Jr.
Charles Bestor
Tom Cori
Robert and Margaret Hazen
Gershon Kekst
Paul and Carolyn Kokulis
Lawrence and Dana Linden
Robert B. Millard
Alvin E. and Honey W. Nashman
Barry Osmond

\$1,000 to \$9,999

Henry H. Amhold
Diane and Norman Bernstein
Anthony J. Cavaliere and Ellen Look
John F. Crawford

Howard C. and Eleanora K. Dalton

Hugh H. Darby
Gordon and Alice Davis
Louis E. DeLanney
Hugo and Margaret de Neufville
Jo Ann Eder
Charles D. Ellis and Linda K. Lorimer
Gary and Charlotte Ernst
Sandra and Andrew Faber
Christopher B. Field and Nona Chianello
Wendy Freedman and Barry Madore
Martin Gellert
Enrique Gittes and Lois Severini
Pembroke J. Hart
John W. and Dori Holaday
Charles B. Hunter
Paul A. Johnson
Peter G. Katona
Gerald D. Laubach
John K. Lim
John D. Macomber
Steven L. McKnight
Richard A. and Martha R. Meserve
Mary K. Montgomery
Frank and Billie Press
Alice Rivlin and Sidney G. Winter
Vera C. and Robert J. Rubin
Eugenia A. and Robert C. Seamans, Jr.
Dan and Maxine Singer
Christopher R. Somerville
Allan Spradling and Connie Griffin
Roselyne C. Swig
Scott B. Tollefsen
Margaret Woodring
Fredrick P. Woodson

Under \$1,000

Jagannadham Akella
W. G. Allaway
David M. Andersen
Joseph P. Ardizzi
James K. Avery

Harry Bacas
Manuel N. Bass
Walter Beach
Brandi Beckner
Harvey E. Belkin
Bradley F. Bennett
Giuseppe and L. Elizabeth Bertani
Daniel Bogenhagen
Daniel H. Borinsky
Kurt R. Borski
Francis R. Boyd
Mrs. Montgomery S. Bradley
Todd and Caroline Brethauer
Robin Brett
Winslow Briggs
Charles L. Bristol
Harold and Naomi Brodsky
Donald D. and Linda W. Brown
Jeanette S. Brown
Louis and Lore Brown
Allan B. Burdick
Gordon Burley
Donald M. Burt
Andrew Butz
Timothy J. Carr
Dana Carroll
Britton Chance
Asit Choudhuri
Ida Chow
Michael P. Cohen
John and Annette Coleman
Jonathan Coopersmith
James and Carolyn Cradler
Valerie K. Craig
William Cramer
Louise M. Crane
John R. and Muriel H. Cronin
Daniel L. Crotty
Martin Czigler
Igor B. Dawid and Keiko Ozato
Vincent J. De Feo
Peter de Jonge
Richard V. Dietrich
John F. Dilley
A. L. Dilonardo
John and Ruth Doak
Bruce R. Doe
Thomas S. Duffy
William H. Duncan
Donald N. and Selma N. Duvick

Esther E. Ecklund
Michael W. Eschenburg
John Farhood
Raul Fernandez
Dorothy Ruth Fischer
Marilyn L. Fogel and Chris Swarth
Frederick Forro, Jr.
Laurence and Frances Fredrick
Fred S. Fry, Jr.
Gladys H. Fuller
Joseph H. Gainer
David and Carolyn Gambrel
Susan Gerbi-McIlwain
Mary H. Goldsmith
Richard H. Goodwin
Jill and Stephen Grant
F. Loyal Greer
Richard Gross
Necip Guven
William and Dorothy Hagar
P. Edgar Hare
Shirley A. Hargraves-Berl
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William K. Hart
Richard S. and Catherine Hartman
J. Woodland Hastings
H. Lawrence and Joanne S. Helfer
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Vera J. Hewitt
Toby M. Horn
Marshall Hornblower, Esq.
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Satoshi Hoshina
Robert F. Howard
Josephine Hudson
Sandra N. Humphrey
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Edwin J. Istvan
John H. Jacobs
Jack C. James
Hiroaki Kagawa
Monica Koch-Muller
David C. Koo
William E. and Teresita Kopka
Olavi Kouvo
Ikuo Kushiro
Ann M. Lacy
Charles Laird

Arlo U. Landolt
Hans Laufer
Arthur LaVelle
Helfer H. Lawrence
Samuel Lawrence
Arthur Lazarus, Jr.
Lavonne Lela
Stewart Lending
F. Harlan Lewis
Kathleen D. Lewis
Mr. and Mrs. Steven L'Hernault
Haifan Lin
Sally Irene Lipsey
Elizabeth Little
Jun K. Liu
Joseph W. Livingston
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Chester B. and Barbara C. Martin, Jr.
Irene and Egon Marx
Mabel B. Mattingly
James M. Mattinson
Dennis and Janet McCormick
Sheila McCormick
Carl R. Merrill
Dennis F. Miller
Lee J. Miller
Gary Mrenak
Thomas A. Mueller
John Reid Murphy
Jack E. Myers
Robert A. Nilan
Peter J. Nind
Adrienne Noe
Edmundo O. Norabuena
Noboru Oba
Michael O'Connor
Goetz K. Oertel
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Shirley Raps
Douglas and Anne ReVelle
Philippe Reymond
Rodney and Josie Rothstein
Douglas and Karen Rumble
Jorge Sahade
Otto Sardi
Akira Sasaki
Maarten Schmidt
Marguerite V. Schneeberger

Allen W. Schuetz
Joyce Schwartz
Kiyoji Shiono
Eli C. Siegel
Virginia B. Sisson
James A. Soles
Lester and Shirley Stein
Malcolm Steinberg
Alan and Bonnie Stueber
Kathleen Taimi
Thomas M. Tekach
George A. and Anita Thompson
Ian Thompson
Norbert and Roslyn Thonnard
Heinz Tiedemann
Peter A. Tinsley
Michael Tobias
Charles H. Townes
Larry N. and Rosalie Vanderhoef
W. Karl and Luella VanNewkirk
Arthur and Anne Vaughan
David Velinsky
Jacob L. and Leah Warner
Andrew Waterman
Johannes Weertman
Edward and Judith White
Gilbert F. White
William M. White
W. Dexter Whitehead, Jr.
Fredrick P. Woodson
Frank K. Wyatt III
Guozhi Xia
Kenzo Yagi
Charles Yanofsky
John and Violet K. Young

GOVERNMENT

Over \$1 Million

National Aeronautics and Space Administration
National Science Foundation
Space Telescope Science Institute
U.S. Department of Energy
U.S. Public Health Service

\$100,000 to \$1 Million

National Oceanic and Atmospheric Administration
U.S. Department of Agriculture
U.S. National Archives and Records Administration
U.S. Office of Naval Research

\$10,000 to \$99,999

Jet Propulsion Laboratory
National Institute for Global Environmental Change,
Western Regional Center

OTHER

\$100,000 to \$1 Million

American Cancer Society

\$10,000 to \$99,999

American Astronomical Society
Biosphere 2
Centre National de la Recherche Scientifique
D.C. Children and Youth Investment Trust Corporation
Elsevier Science B.V.
Institute of Earth Sciences, Academia Sinica
Life Sciences Research Foundation
National Academy of Sciences
National Health Museum

\$1,000 to \$9,999

Yale University



THE DIRECTOR'S REPORT:

CASE and First Light Science for the Nation's Children

First Light is growing up! This fall, 24 middle school students in grades six through eight from Washington, D.C., public schools (DCPS) and charter schools were accepted into the program. Toby Horn, who is in charge of secondary programs at CASE, is the lead instructor. Julie Edmonds (Fig. 1), Inés Cifuentes, and Maxine Singer assist "Dr. Toby" with instruction. In addition, two DCPS high school students—Dominic Gasaway, a former First Light student, and Kendra Hardman—joined us as interns. On Saturday mornings we concentrate on the diversity of life and planetary science in the CASE laboratory classrooms (Fig. 2). In the afternoons, we explore science in the city through field trips to museums, natural environments, and labs in the D.C. metro-

politan area. The group has already visited Carnegie scientist James Scott at the Geophysical Laboratory (Fig. 3). Scott and collaborators adapt the tools of high-pressure physics to microbiology to study how common organisms are able to live and thrive under unusually high-pressure conditions. The First Light group will visit other Carnegie labs in the near future, and a trip is planned to the University of Maryland, Baltimore County—whose president, Freeman Hrabowski, is a Carnegie trustee—to get the students thinking about college.

Over the past several years, CASE has played a major role in the education and public outreach activities for two of the institution's NASA-funded projects: Carnegie Astrobiology (part of NASA's



Fig. 1. On a Saturday morning, Julie Edmonds (back right) instructs First Light students in the art of extracting DNA from strawberries.



Fig. 2. First Light students Sharmaine and Leshia prepare a dish with seeds to investigate the effect of gravity on plant growth.



Astrobiology Institute, or NAI) and the MESSENGER Mission to Mercury. Sean Solomon, director of the Department of Terrestrial Magnetism, is the principal investigator for both of these multi-institutional programs. One of CASE's goals is to bring the excitement of Carnegie scientists' research and discovery to young people, teachers, and the public. Previously, we developed a variety of teaching materials and booklets for these projects, including two award-winning posters. All of the products have had widespread national distribution through organizations such as the National Science Teachers Association, NASA, and the Geological Society of America.

This year we developed innovative, interactive displays (kiosks) based on the magnificent artwork and instructional materials featured on posters for deep sea vent astrobiology and MESSENGER. The display artwork includes several elements that, when touched, activate an embedded computer monitor to show informative video footage on the chosen topic. The displays came about through close collaboration between CASE staff and Carnegie scientists. The kiosks are self-contained and designed to travel to conferences, museums, libraries, and science centers (Fig. 4).



Fig. 3. Geophysical Laboratory staff associate and microbiologist James Scott (right) engages First Light students with a DNA experiment.

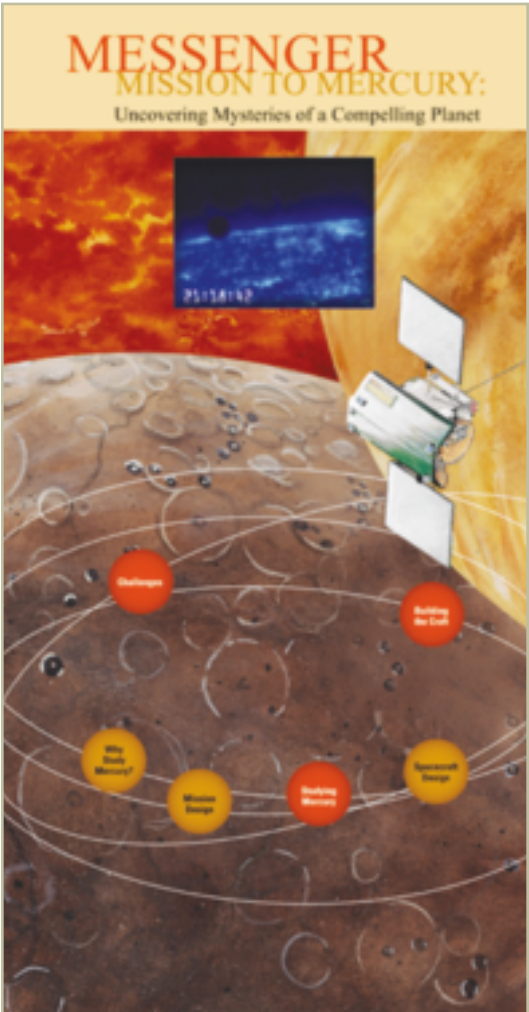


Fig. 4. In the coming years this interactive kiosk, which CASE developed for the MESSENGER Mission to Mercury, will travel the country to museums, universities, libraries, and conferences. It explains the challenges that will be faced and the science that will be accomplished during the mission to the innermost planet. The craft is due to begin orbiting Mercury in March 2011.

Our astrobiology kiosk was chosen by the National Science Foundation to be featured in the ESTME (Excellence in Science, Technology, and Mathematics Education) Week Expo in March 2004, which is part of the Department of Education's Science Summit. It was also featured at the national astrobiology meeting, AbSciCon, at NASA Ames Research Center in California and has been on loan to the University of Tennessee as well as the museum at Pennsylvania State. In 2005 the NAI team at the University of Hawaii will feature the kiosk in several public libraries as part of a multi-island public outreach effort. The MESSENGER kiosk, meanwhile, was featured at the August 2004 launch-night celebrations and was on display at the Brevard Community College Planetarium through December. In January 2005 it moved to the Maryland Science Center in Baltimore.

In the year leading up to the MESSENGER launch, CASE staff collaborated with educators from the Challenger Center for Space Science Education to produce a comprehensive series of lessons on "Staying Cool," something the spacecraft must do if it is to survive its journey to Mercury. These lessons have been used to train 30 teachers to become MESSENGER Fellows. Once trained, they are committed to conducting workshops for other teachers. Over the next few years almost 1,000 teachers nationwide will be trained in the use of these classroom materials.

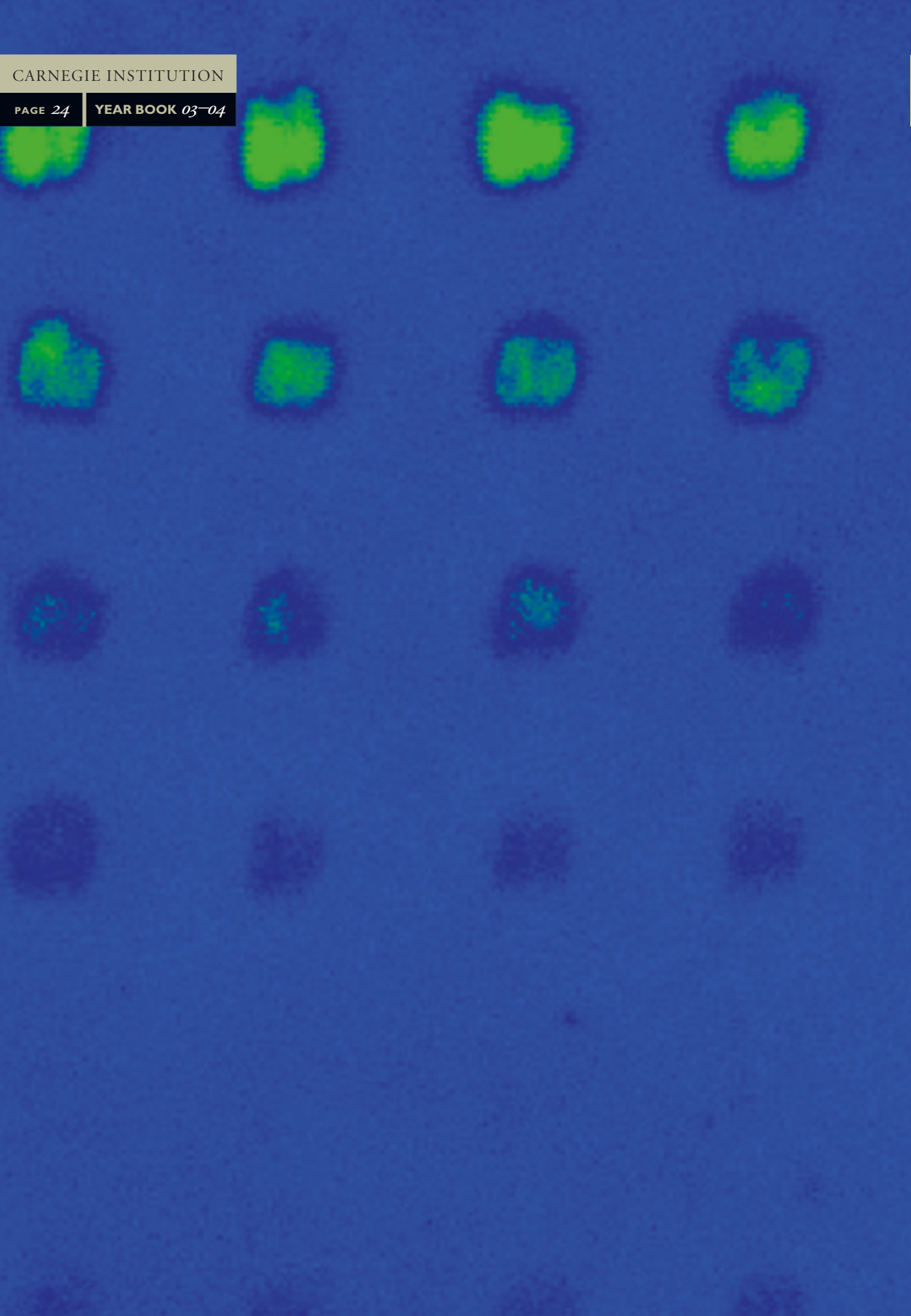
The CASE staff takes great pride that our influence has spread well beyond the local area over the last decade and a half. Through the many teachers who have been involved in our programs, we spread the discoveries of Carnegie scientists to students all over the country, and we look forward to the day when some "First Lighters" become scientists themselves.

—*Inés Lucía Cifuentes, CASE Director*
Julie Edmonds, CASE Associate Director
Toby Horn, CASE Secondary Programs




Fig. 5. Toby Horn, who heads CASE's secondary programs (right), takes First Light students to the James Scott lab at Carnegie's Geophysical Laboratory. Scott showed the student the facilities to culture deep bacteria.





THE DIRECTOR'S REPORT



Research at the Geophysical Laboratory (GL) into the fundamental physics, chemistry, and biology of the Earth and other planets continues to progress. I have selected research results carried out this past year that illustrate the exciting directions we are pursuing.

Prebiotic Chemistry on the Early Earth

A GL predoctoral student, Nick Platts, recently received his Ph.D. from Rensselaer Polytechnic Institute investigating a novel theory that directly addresses one of the most intractable problems in origins-of-life research, namely, identifying a transitional mechanism between the dilute “prebiotic soup” of small organic molecules in Darwin’s “warm little pond” and the modern concept of a protobiological “RNA-world” based on informational oligomers of nucleic acids. Nick has proposed a testable chemical model based on the self-assembling behaviors of polycyclic aromatic hydrocarbons (PAHs)(Fig. 1), which are known to be ubiquitous in space, in meteorites, and in numerous terrestrial geologic settings, making them likely to have been abundant in the Earth’s prebiotic environment.

PAHs self-assemble into stacked arrangements because of the weak bonding of the atoms across their planar structures. PAHs of roughly similar size and shape stack above each other, such that

their edges are roughly aligned. Functional groups, including -OH or -CO, at the edges of the stack then form hydrogen bonds to other planar molecules including purines and pyrimidines, the building blocks of RNA and DNA. These attached purines and pyrimidines stack in layers 0.34 nanometer (nm) apart, exactly the distance found in RNA. In addition, their orientation has the proper portion of the molecule directed outward, facilitating the construction of long strands of RNA once detached from the PAH host. The PAH stack could also serve as a strong absorber of ultraviolet light, which would protect the selected

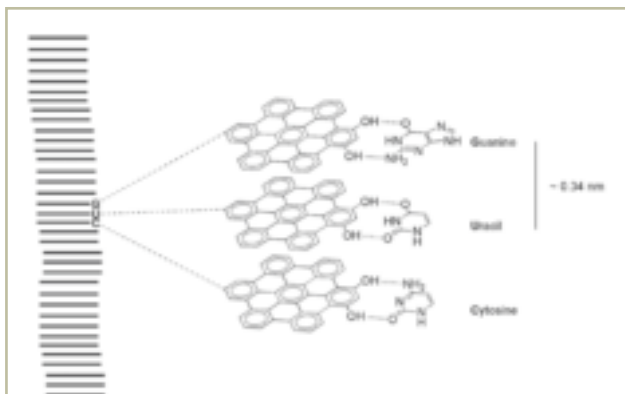


Fig. 1. Three nucleobases are shown hydrogen-bonded to hydroxy functions in the edge structures of PAH molecules in a stacked array. The PAH stack edge is a phase boundary between the aromatic cores of the PAHs and the surrounding aqueous media of Darwin’s “warm little pond.”

Left: Antibody microarrays look for hundreds of different molecules at the same time and are used in biomedical research to investigate genes. Andrew Steele’s group is devising ways to use them to find microbes in rocks. Their ultimate goal is to use microarrays in the search for life on Mars (see Figure 4).

and concentrated assemblage of heterocycles from photolytic breakdown. Further work is in progress in the lab to test the viability of Nick’s ingenious hypothesis.

Organic Material in the Solar System

George Cody has been applying solid-state nuclear magnetic resonance (NMR) spectroscopic techniques to analyze the insoluble organic matter (IOM) in meteorites. Figure 2 shows the results for four different carbonaceous chondrites: EET92042 (CR2), Orgueil (CI1), Murchison (CM2), and Tagish Lake. These experiments reveal considerable variation in bulk organic composition. The fraction of aromatic carbon increases as EET < Orgueil < Murchison < Tagish Lake. The increases in aromatic carbon are largely offset by reductions in aliphatic hydrocarbons, alcohols, amines, and ethers. These data are consistent with the primary parent body reactions being low-temperature chemical oxidation.

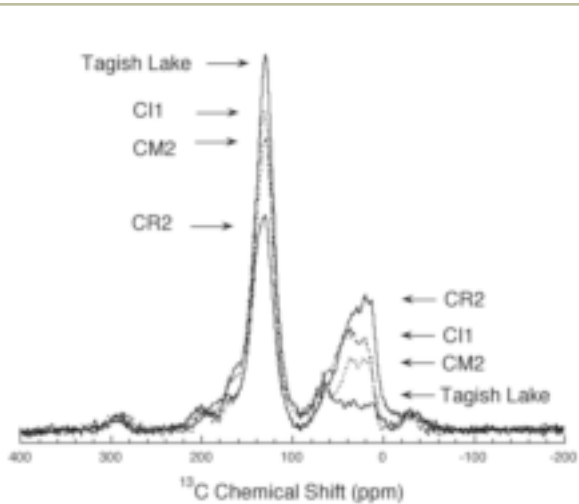


Fig. 2. This overlay shows NMR spectra of four meteorite insoluble organic matter fractions. Each spectrum is normalized to the total spectral intensity. The pronounced peak at ~129 parts per million (ppm) corresponds to aromatic carbon. The broad peak spanning ~10–90 ppm corresponds to aliphatic hydrocarbons, alcohols, amines, and ethers.

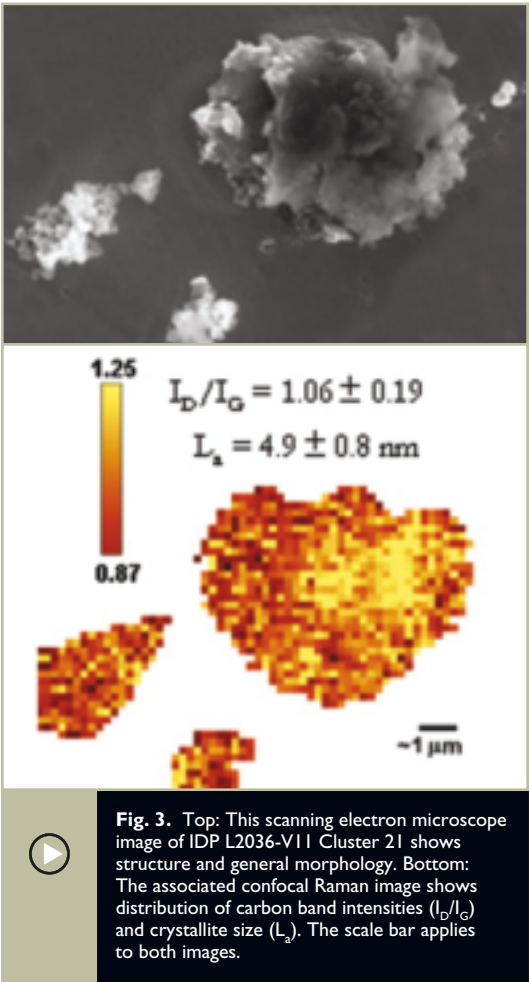


Fig. 3. Top: This scanning electron microscope image of IDP L2036-V11 Cluster 21 shows structure and general morphology. Bottom: The associated confocal Raman image shows distribution of carbon band intensities (I_D/I_G) and crystallite size (L_a). The scale bar applies to both images.

Interplanetary dust particles (IDPs) are small, fluffy particles from space generally collected in the atmosphere. They are typically several microns in diameter and contain carbon and other materials with structure on a scale of tens to hundreds of nanometers. Andrew Steele’s group has performed new laser Raman imaging that shows that the carbon phase is heterogeneous on a small scale, by producing maps of the distribution of carbon material. This work represents the first time that the distribution of carbon in IDPs has been directly imaged (Fig. 3). A large population of IDPs will be measured to obtain information on the initial temperature and carbon concentration of the primordial gas from which the IDPs condensed.

Looking for Life in All the Right Places

An antibody microarray can search for hundreds of different molecules simultaneously from just a few microliters of sample. These microarrays are generally used to investigate patterns of human gene expression in biomedical research, but Andrew Steele and his group are using them to develop a method for microbial detection in geological samples. They spiked simulated regolith with lyophilized *Escherichia coli*, labeled with a fluorescent dye, and applied it to the microarray surface (Fig. 4). The spiked regolith elicited a high signal for lipopolysaccharide (LPS) and GroEL, two biomarkers expressed in *E. coli*. Nonspiked regolith showed a low signal for these and nine other biomarkers. Steele's group has also used an antibody microarray to identify fossil proteins in bones ranging from hundreds of thousands to millions of years old. This study is believed to be the first time that protein microarrays have been used to detect fossil biomarkers. Steele is developing such techniques for an instrument to search for biomarkers on Mars, called Modular Assays for Solar System Exploration (MASSE), in collaboration with the Marshall Space Flight Center, Oceaneering Space Systems, the Marine Biology Laboratory, North Carolina State University, and Montana State University.

Life under Stress

James Scott is studying how life responds to changes in water when water is subjected to conditions of extreme pressure and temperature. The properties of water allow the biochemistry of life to flourish on Earth, but the properties change drastically with extremes of temperature and pressure (Fig. 5). James is utilizing large-volume diamond-anvil cells and new protocols to isolate and culture *Escherichia coli* K12 cells after recovering them from high-pressure experiments. The experiments last up to 32 days and have pressures up to 4 kilobars at ambient temperature. He has found that cells exposed to this stress adapt, probably by shutting down all nonessential energy-consuming processes, which conserves their energy for essen-

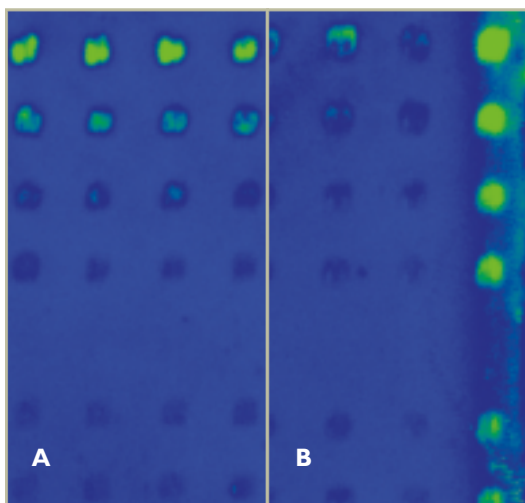
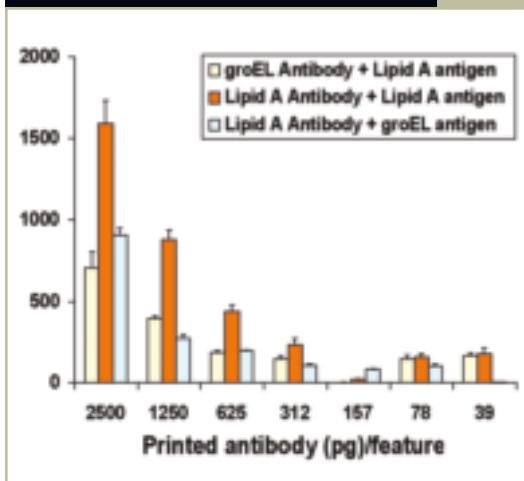


Fig. 4. This simple microarray detects lipopolysaccharide (LPS). Features are printed with an anti-LPS antibody (A) and an anti-GroEL antibody as a negative control. The microarray was incubated with LPS, washed, incubated with an Alexa⁶³³ conjugated goat anti-rabbit antibody, washed, and then scanned using a 635 nm laser and fluorescence emission detected between 650 and 690 nm.



tial metabolic processes. Cells exposed to kilobar pressures appear to be unable to “bounce back” once pressure-adapted. James is now working to determine if the adaptation of *E. coli* to pressure is due to short-term mechanisms or to the more profound “evolutionary” changes that have been reported by others when cells are exposed to sub-lethal stresses.

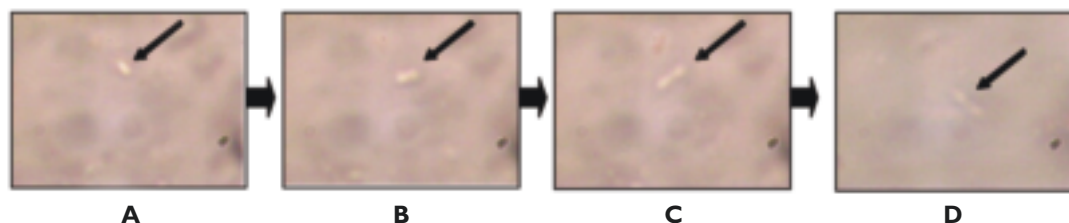


Fig. 5. This series of time-lapse images (~20 min between frames) shows a single cell dividing at ambient conditions after decompression from 1.4 gigapascals (GPa) in a diamond-anvil cell. The observations confirm the viability of the organism at very high pressures.

Mission to the Core

Geophysical and geochemical observations indicate that a substantial amount of light elements such as S, Si, O, and C may be mixed within the Fe core of planets like the Earth and Mars. Yingwei Fei has been investigating the possible mechanism for the incorporation of these light elements into the cores by studying the melting relations and solubility of the light elements in metallic Fe at high pressures and temperatures. He and former postdoctoral fellow Chrystele Sanloup have conducted a series of experiments to show that if the size of the planet is such that the maximum pressure encountered was below 14 gigapascals (GPa) during its differentiation, then silicon is unlikely to be a light element of its core. However, sulfur is likely to be present in large quantities. Jupiter's moon Ganymede, and Mars, could well be in this category of "low-pressure" differentiated planetary bodies.

Rus Hemley and Wendy Mao (University of Chicago) have determined the properties of iron hydride (FeH_x) up to 52 GPa to constrain the aggregate shear velocity and shear modulus for comparison with seismic observations of the Earth. A loss of magnetism was observed at 22 GPa, which is lower than theoretically predicted but is consistent with the observed anomalous velocity

behavior. The results confirm that FeH_x could be a major light element bearing phase for explaining the core density deficit relative to pure iron. Formation of FeH_x by reaction with water would be expected to leave a signature in the mantle.

Deep Hydrocarbons

Understanding the chemistry of carbon at the high pressures and temperatures that prevail within the Earth has a long and controversial history. Terrestrial carbon exists in several forms: native, oxidized, and reduced in a wide variety of hydrocarbons. During the past year, Rus Hemley and former postdoc Henry Scott found that methane was formed from FeO , CaCO_3 -calcite, and water at pressures between 5 and 11 GPa and temperatures ranging from 500 to 1500°C (Fig. 6). The result demonstrated the existence of abiogenic pathways for the formation of hydrocarbons in the Earth's interior, which suggests that the hydrocarbon budget of the bulk Earth may be larger than conventionally assumed. The finding is particularly relevant in light of the recent identification of methane at parts-per-billion levels in the atmosphere of Mars. It is not known if methane in the Martian atmosphere is produced volcanically or biologically.

Inside Giant Planets

Burkhard Militzer is working with Bill Hubbard (University of Arizona) and Dave Stevenson (Caltech) on a theoretical investigation of the interior structure of giant planets and how the structure has evolved over time. Since there is no direct way to probe the interior of giant planets, understanding relies on theoretical modeling. The modeling requires three input parameters: the chemical composition of the planet, its gravitational moments, and an accurate equation of state for the hydrogen-helium mixture in the planetary interior. Information on composition and gravitational moments has come from the *Galileo* and *Cassini* spacecraft missions. Militzer's team is focusing on deriving a more accurate equation of state for hydrogen-helium mixtures. Laboratory methods are not yet able to reproduce the pressure-temperature (P-T) ranges deep inside the giant planets, so

Militzer has applied new quantum Monte Carlo techniques for the first time to improve the best model previously available to help determine the interior structure of Jupiter.

New Materials

Storage of hydrogen

The long-term plan to transform our economy from its reliance on fossil fuels has generated new interest in hydrogen. One of the technological obstacles to making hydrogen economically viable, however, is the problem of storage. Compared with gasoline, a tank of hydrogen gas at practical pressures requires a much larger volume. Therefore, a variety of different materials have been proposed to store hydrogen by using chemical compounds or by physical absorption. A good hydrogen storage material must store 5% hydrogen by weight

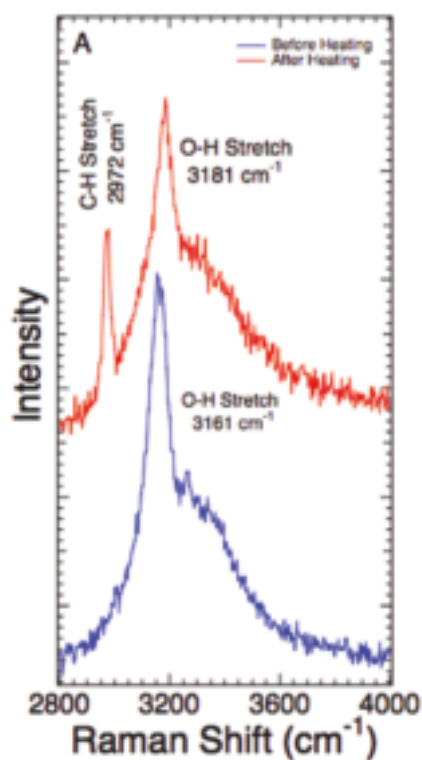
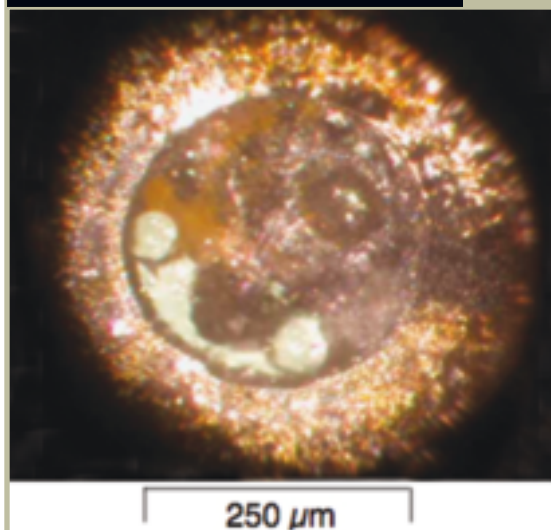


Fig. 6. Left: Raman spectra from heating FeO, calcite, and water at 5.7 GPa and 1500°C shows the appearance of the C-H stretch upon heating. Below: Methane bubbles formed upon decompression to approximately 0.5 GPa. Bubbles are visible near the bottom left side, and slightly right of center.



reversibly and take up a reasonably small volume. Viktor Struzhkin, Ho-kwang Mao, Wendy Mao, and Rus Hemley are investigating one of the most promising such materials: hydrogen in clathrates—weakly bound molecular cages within which hydrogen is trapped. Hydrogen retained by the weak van der Waals forces in these solids can be readily released. Clathrates can retain an enormous amount of hydrogen; for example, $(\text{H}_2)_4(\text{CH}_4)$ holds 33.4 wt% molecular hydrogen (50% atomic H), which is far above Department of Energy targets.

New materials from high pressure

New materials continue to be discovered under pressure, and a growing number of these have been recovered to ambient conditions. There has been considerable interest in the creation of new nitrides, motivated by the search for new superhard compounds, electronic materials (such as superconductors), and optoelectronic materials. The first nitride of a noble metal, platinum nitride PtN, has been synthesized at GL. The material has intriguing physical properties, including very high incompressibility, and it is a semiconductor. And most remarkably, after synthesis at very high pressures it can be recovered at ambient conditions.

Developments in CVD single-crystal diamond

Progress in the creation of large single-crystal diamonds by chemical vapor deposition (CVD) at GL was particularly notable this year. A process has been perfected to fabricate single-crystal diamonds by microwave plasma CVD at very high growth rates. During the past year, crystals up to 4.5 millimeters (mm) in thickness have been fabricated at growth rates as much as two orders of magnitude higher than those produced by conventional polycrystalline CVD methods. As grown, the material has high fracture toughness and on annealing its hardness can increase dramatically, reaching values some 50% higher than conventional diamond. This work has gained tremendous attention worldwide and has resulted in three patent-application filings this year. Anvils have been fashioned from these new CVD diamonds at GL, and they have been used in high-pressure experiments at multimegabar pressures.

—Wesley T. Huntress, Jr.



Fig. 7. Members of the Geophysical Laboratory staff are shown in November 2004. First row (from left): Andrey Bekker, Roy Dingus, Sue Schmidt, Adelio Contreras, Pedro Roa, Pablo Esparza, Shuhei Ono, James Scott, Jennifer Eigenbrode, Marc Fries. Second row: Valentina Degtyareva, Olga Degtyareva, Wes Huntress, Marjorie Imlay, Maceo Bacote, Tim Jenkins, Jennifer Snyder, Morgan Phillips, Jinfu Shu, David George, Nabil Bector, Catherine Corrigan. Third row: George Cody, Ron Cohen, Doug Rumble, Yingwei Fei, Bobbie Brown, Steve Coley, Burkhard Militzer, Shantanu Keshav. Fourth row: Muhetaer Aihaiti, Brad Chen, Paul Meeder, Rus Hemley, Chih-Shiue Yan, Lars Ehm, Xiao-Jia Chen, Xianwei Sha, Chris Hadidiacos, Razvan Caracas, Alex Corgne, Charles Hargrove, Steve Gramsch, Yufeng Ren, Li Zhang, Bjørn Mysen, Jung-Fu Lin, Yang Song. Fifth row: Neil Irvine, Gary Bors, John Straub, Bill Key, Aravind Asthagiri, Gudmundur Gudfinnsson, Takuo Okuchi, Jake Maule, Mathieu Roskosz, Eugene Gregoryanz, Marilyn Fogel, Viktor Struzhkin, Katherine Cooney, Gotthard Sági-Szabó, Garrett Huntress. Missing from the picture: Przemyslaw Dera, Shaun Hardy, Robert Hazen, Steven Jacobsen, Agnes Mao, Dave Mao, Marcus Origlieri, Andrew Steele, Jan Toporski, Merri Wolf, Zhigang Wu.



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⁸From July 5, 2003

⁹From July 1, 2003

¹⁰From December 1, 2003

¹¹From July 30, 2003

¹²From July 14, 2003

¹³From April 12, 2004

¹⁴To April 14, 2004

¹⁵From January 5, 2004

¹⁶From October 14, 2003

¹⁷To June 30, 2004

¹⁸To November 2, 2003

¹⁹From December 22, 2003

²⁰To October 11, 2003

²¹To June 30, 2004

²²To July 1, 2003

²³From February 23, 2004

²⁴To August 13, 2003

²⁵To November 8, 2003

²⁶To February 2, 2004

²⁷From July 1, 2003

²⁸To August 11, 2003

²⁹To August 27, 2003

³⁰From January 2, 2004

³¹Joint appointment with DTM

³²To June 15, 2004

³³From January 2, 2004

³⁴To January 23, 2004; joint appointment with DTM

³⁵To June 7, 2004

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THE DIRECTOR'S REPORT

“ONE MUST SHOW THE GREATEST RESPECT
TOWARDS ANY THING THAT INCREASES EXPONENTIALLY,
NO MATTER HOW SMALL.”

—Garrett Hardin, 1968

Single-celled, photosynthetic prokaryotic organisms, called cyanobacteria, have been around for at least 3 billion years (frontispiece). Although the early evolution and phylogeny of these organisms is still a matter of study and debate, there is little doubt that cyanobacteria have played and continue to play a major role in forming the atmosphere and structure of ecological communities on Earth. Cyanobacteria are major producers in the aquatic habitats of the world, and as a consequence of an endosymbiotic association with a unicellular protist, they evolved into the modern-day plastid (the plant powerhouse for photosynthesis). Understanding these ancient, exquisitely complex and widely distributed organisms has been the focus of the laboratories of staff member Arthur Grossman and adjunct staff member Devaki Bhaya for several years.

Arthur's laboratory has made a number of landmark discoveries concerning the molecular underpinnings that govern how cyanobacteria and other algae intercept light energy and cope with both their light and nutrient environments. For example, his laboratory first isolated light-harvesting genes from the diatoms and demonstrated that they were related to the light-harvesting genes of vascular plants. His group also demonstrated that phytochrome-like photoreceptors in some cyanobacteria can serve to sense the light wavelengths of the environment—information used to

tune the composition of the light-harvesting complex for optimal light absorption.

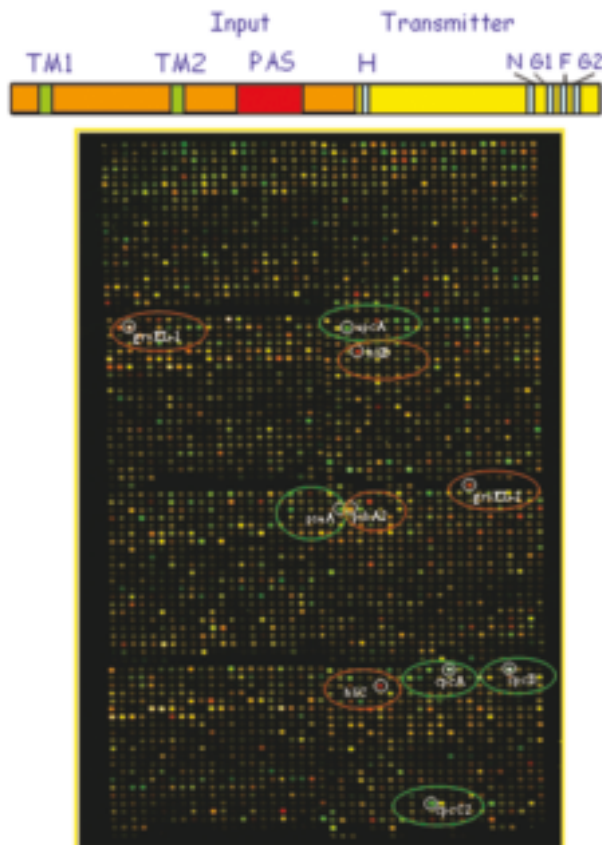
Devaki first arrived at the department several years ago as a Rockefeller Fellow and visiting investigator from Nehru University in New Delhi, India, to learn about these remarkable creatures. Her first visit was followed by several others and in the mid-1990s, when the initial cyanobacterial genome sequences became available, Arthur and Devaki collaborated on a joint project to exploit genomic information to understand molecular mechanisms by which cyanobacteria acclimate to environmental change. It is astounding that with a repertoire of only about 3,000 genes (some have as few as 1,500 genes), cyanobacteria are able to survive an array of suboptimal conditions. Perhaps reaching the ripe old age of 3 billion makes them pretty good at roughing things out!

There are now a variety of sophisticated molecular and genomic tools that make cyanobacteria important, tractable model systems for exploring acclimation both in the laboratory and in situ. For instance, strong genetic and molecular technologies have led to the identification of the putative central stress regulator designated NblS (also known as DspA or Hik33; important genes and their proteins often have more than one name). This protein appears to sense both nutrient and light conditions, probably by sensing both the redox

Left: This canyon in Glacier National Park has a white layer of carbonate rock, which is a reef-scale bed of stromatolite fossils that formed a little over a billion years ago at the margin of an inland sea. These reefs were most likely constructed by cyanobacterial mats that lived in intertidal or shallow-water habitats. Photosynthesis by such extensive microbial communities would have contributed massively to the oxygenation of Earth during the Precambrian era. (Image courtesy Dave Ward, Montana State University.)



Fig. 1. This microarray analysis shows the structure of NblS/Hik33 and the effect of inactivating the gene on global gene expression in *Synechocystis* PCC6803. The structure of NblS/Hik33 is shown at top. The protein has both an input and a transmitter module. The input module has transmembrane domains (TM1 and TM2) and a PAS domain. The PAS domain has the potential to bind small molecules, such as flavins that are involved in sensing varied environmental conditions. The transmitter module consists of a histidine kinase (the N, G1, F, and G2 region) that can undergo an autophosphorylation at the histidine residue marked (H). The phosphorylation activity is controlled by the sensing activity of the input module. The microarray in the lower part of the figure shows the consequence of inactivation of the gene encoding NblS/Hik33 in *Synechococcus* on global gene expression. Many transcripts associated with acclimation of the cells to high light conditions are constitutively active (e.g., *psbA2*, *hliB*, *groEL-2*), while others that are normally suppressed in high light are constitutively low (*cpcC2*). The mutant behaves as if it is always experiencing high light stress.



state of the cell and possibly by absorbing blue/UV-A light (Fig. 1). The protein has two transmembrane domains, a PAS domain that might bind a flavin chromophore and a histidine kinase domain. Postdoctoral fellows, and most recently Chao-Jung Tu, were able to show that a mutant aberrant for NblS is unable to acclimate to both the light and the nutrient environment, which was graphically demonstrated by microarray analysis of both the wild type and the mutant strain (Fig. 2). Studies of this central regulator have also led to ideas concerning the evolution of blue-light photoreceptors from electron transfer components and redox sensors. Figure 2 depicts the possible evolution of NblS from an electron transfer component to its proposed function in maintaining the homeostasis of the cell by sensing both cellular redox status and blue/UV-A light signals.

Microarray analysis of cyanobacterial gene expression provides a detailed snapshot of the workings of a cyanobacterial cell. By combining these snapshots, one can create what one might fancifully call an album, which helps define the major events in the life of a photosynthetic prokaryote, and how it reacts when it is treated badly. More precisely, these analyses are allowing researchers to map global changes in the expression of genes as environmental conditions change, and to combine these analyses with both computation and bioinformatic approaches, emerging fields that both Arthur and Devaki embraced several years ago. Collaborations with Jan Mrazek and Sam Karlin of the Department of Mathematics at Stanford University and with Daniel Vaulot's group at Station Biologique in Roscoff, France, have enabled Arthur and Devaki to exploit the power of computational

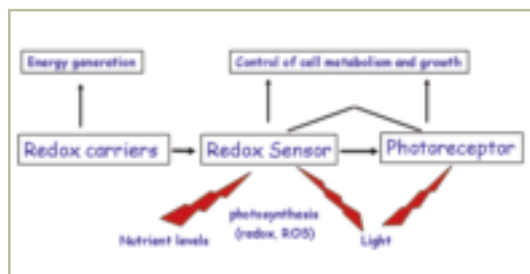


Fig. 2. Sensors, such as NblS/Hik33, may have evolved from redox carriers (involved in energy production) to redox sensors (involved in sensing the intracellular redox state), or to photoreceptors (sensing light conditions, especially blue/UV-A light). Some sensing molecules may be able to perceive multiple inputs such as redox levels as well as the characteristics of the light environment (through the direct absorption of light energy by chromophores that bind to the PAS domain).

tools to make predictions about the evolution and gene expression potential for whole genomes. The list of fully sequenced cyanobacterial genomes is now over 15 and spans the gamut from unicellular to filamentous, lake to open ocean-dwelling, free-living to symbiotic, benign to toxic, and mesophilic to thermophilic. Devaki and Arthur plan to mine this expanding well of diversity and use the information in creative ways that marry genome-based hypotheses to wet-lab experimentation.

The use of rapidly growing, genetically tractable organisms has led to numerous fascinating discoveries at the molecular and mechanistic level. For instance, it had been documented over a hundred years ago that certain microorganisms move toward or away from a light source (a phenomenon often called phototaxis). Despite several early attempts at a detailed characterization of this phenomenon, the molecular and biochemical details of motility and photoperception have only recently been uncovered. Using a method for randomly disrupting genes in the unicellular cyanobacterium *Synechocystis*, Devaki was able to visually screen for mutants, which were aberrant for phototaxis response (Fig. 3). Surprisingly, this tiny organism seems to use a very large number of genes (a minimum of 60) to control motility and phototaxis.

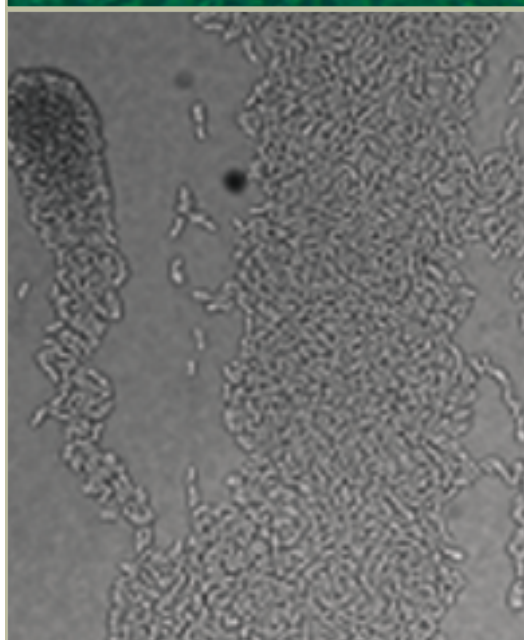
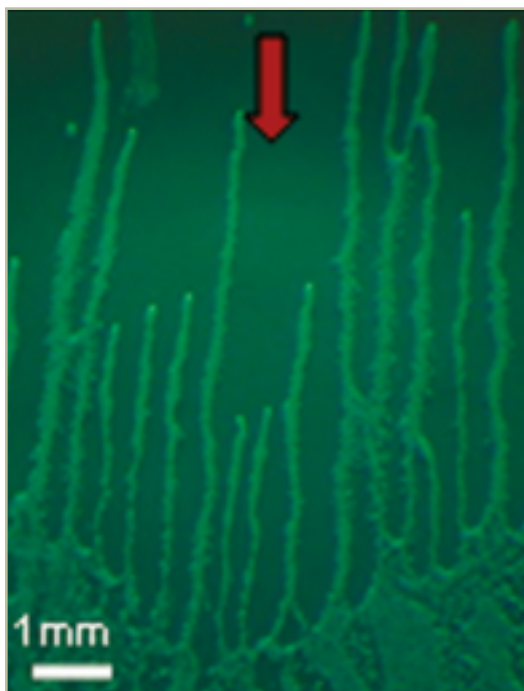


Fig. 3. This motility plate assay (top) shows phototaxis of the thermophilic cyanobacterium *Synechococcus*. Finger-like projections of cells move toward red light. At higher magnification (bottom) of one of the fingers, individual cells are evident.



Fig. 4. Frontiers in Integrative Biological Research (FIBR) participants pose at the first FIBR workshop held in July 2004.



Fig. 5. Mushroom Spring is a typical hot spring with the boiling geyser at center and the cooler channels where orange mats containing cyanobacteria are growing at temperatures around 50-60°C.

The cell appears to use a red-light photoreceptor (similar to the phytochrome used for chromatic adaptation) to track the direction of light, which in turn signals to specific surface appendages called pili that pull the organism in the direction of the light. This movement is exquisitely sensitive to light quality and quantity. Unraveling the ways in which a bag full of genes and gene products control both motor function and directional aspects of movement is just beginning.

In addition to a laboratory-based approach to understanding adaptation, Arthur and Devaki have become interested in the degree to which organisms encode functions that cannot be identified in the narrow range of growth conditions available in the laboratory. As more and more genomes are sequenced, it is becoming clear that a large number of genes are termed hypothetical because they have not been assigned any function. These may well encode proteins that assist microorganisms in coping with particular environmental challenges. However, it may be difficult, if not impossible, to unravel the role of many of these hypothetical genes without venturing into the environment where these organisms are currently found and where they have evolved. The development of microscale tools to precisely measure environmental parameters, coupled with high-throughput molecular techniques to evaluate the biological state of a cell or community of cells in situ, makes this direction both feasible and attractive.

Recently Arthur and Devaki have begun to explore in situ molecular analyses of cyanobacteria and cyanobacterial communities in collaboration with a diverse scientific team including microbial ecologist Dave Ward of Montana State University, John Heidelberg of the Institute for Genomic Research (TIGR), evolutionary biologist Fred Cohan, Sue Rhee of Carnegie, and Michael Kuhl of Denmark (Fig. 4). In a five-year program funded by the National Science Foundation Frontiers in Integrative Biological Research (FIBR), they hope to address basic questions about the evolution and adaptation of microorganisms in a well-studied and unique niche—the natural hot spring microbial mat community systems in Yellowstone National

Park (Fig. 5). These mat communities, which have been studied for decades by microbiologists who view them as models for understanding fundamental aspects of microbial community ecology, occur in the effluent channels of alkaline siliceous springs at temperatures ranging from 88°C to 42°C (the cyanobacterial component of the mat extends to 74°C). Microscopically, the mats appear simple, constructed primarily of a unicellular cyanobacterium considered to be of the *Synechococcus* genus, and a filamentous green, non-sulfur-like bacterium resembling *Chloroflexus* (Fig. 6). However, direct 16S rRNA analysis of the community gives a more complex but realistic view of the mat population. There appear to be a variety of closely related, predominant *Synechococcus* genotypes, which are distantly related to a readily cultivated thermophilic *Synechococcus* strain. Interestingly, the cyanobacterial strain most easily cultivated from the mat is not the predominant species and bears significant similarity to a thermophilic strain that dominates the hot springs in Japan. The extent of diversity in the mat is not known, but there appear to be at least several related *Synechococcus* genotypes that are distributed in an orderly manner along both thermal

and vertical (light) gradients. They seem to be associated with ecologically distinct populations, which are likely uniquely adapted to temperature and light.

Many features of the mat community make it ideal for combining direct population genetics analyses, microsensor probing of gas and nutrient conditions, and microarray (and qPCR) examination of gene expression. This multidisciplinary approach has already triggered a powerful synergy that weaves together diverse information providing a more holistic view of the population and physiological dynamics of the mat communities. There is a rapidly growing interest in moving powerful genomic, evolutionary, and biophysical technologies to the field since it is becoming clearer that the axenic laboratory environment may not provide a realistic view of the physiology of cells as part of microbial communities in a complex and dynamic nutrient and light environment. The mat exhibits well-defined physical/chemical gradients, which can be measured at the microscale by exquisitely sensitive and highly specific microsensors. Microsensors and classical and newer molecular

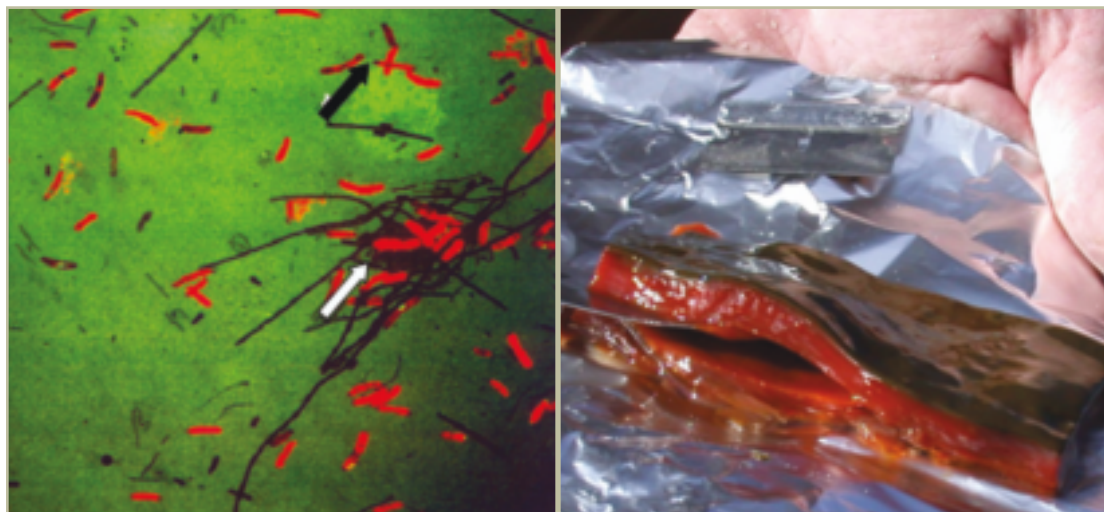


Fig. 6. The left panel shows a confocal microscope image of cells isolated from the microbial mat. The rod-shaped cyanobacterial cells are red because of autofluorescence (black arrow), while the other *Chloroflexus*-like filaments (white arrow) are not fluorescent and create a tight mesh. Cyanobacteria often appear to be associated with these filaments in the mat. The right panel is a close-up of a cross section of the mat. The top green layer contains the cyanobacteria; the orange layer below contains heterotrophs and dead cells.



techniques can be used for quantifying respiratory and photosynthetic activities, analyzing biomass, determining the distribution of the different organisms within the mat, and understanding the dynamics of the population as the environmental conditions change. This approach will be especially interesting with respect to the day-night cycle: organisms go from an oxygenic environment during midday when rates of photosynthesis are high, following microaerobic conditions as the intensity of the Sun declines, and to anaerobic conditions during the evening. These dramatic changes will require molecular switches that completely alter metabolic processes in the cell.

Genomic sequences from two cyanobacterial strains adapted to 60°C and 65°C are now complete, and we have begun to get a first glimpse at how these genomes are arranged and organized. Surprisingly, there is almost no synteny between the genomes of the two analyzed strains. There is relatively little known about gene expression and

gene content of thermophilic cyanobacteria, even though it is possible that the origins of life were first nucleated in a hot spring-like environment and that these organisms are at the base of the tree leading to the evolution of vascular plants. Obviously, the proteins of these thermophilic organisms have evolved to be stable at high temperatures, which raises the exciting possibility that in the future we can understand and possibly exploit the unique characteristics of these proteins. Within the year, microarrays for probing gene expression both in laboratory cultures and in situ will become available. This approach will provide insights into a number of challenging questions: How different is gene expression within the in situ mat milieu compared with the “tamed” laboratory cultures? How does gene expression change as temperature varies along the horizontal gradient of the mat and as light changes along the vertical gradient of the mat? How diverse is the cyanobacterial population within the mat? How diverse is the genome organization? Are genes transferred between organisms within the community? Are there ecotypes that are better adapted to specific temperature niches, and what are the major factors that contribute to the ability of a strain to thrive at a specific temperature? What factors foster communication among different subpopulations of organisms in the mat, and what “communication molecules” are critical? What are the molecular switches that control the metabolic machinery of the cell as the mat is transformed from an oxygenic to an anoxygenic environment? Although it may take years before these questions are answered in depth, the process has been started, and it promises to be an exciting journey.

—Christopher Somerville,
with Arthur Grossman and Devaki Bhaya

Fig. 7. Arthur Grossman and Devaki Bhaya pose in front of one of the many hot springs at Yellowstone National Park.



Related Websites:

http://carnegiedpb.stanford.edu/research/research_bhaya.php
http://www-ciwdpb.stanford.edu/research/grossman2003_rev1/index.html

Hotspring project:

<http://fumarole.stanford.edu/>
<http://landresources.montana.edu/FIBR/>



Fig. 8. Members of the Department of Plant Biology staff are shown. From left, first row standing: Dominique Bergmann, Melissa Lim. Sitting: Ying Sun, Michelle Facette, Meghan Sharp, Debbie Alexander, Khar-Wai Lye, Miguela Torres, John Emery, Sonja Vorwerk, Rebecca McCabe, Monica Stein, Paul Sterbentz, Wirulda Pootakham, Chung-Soon Im. Second row standing: Thorsten Hamann, Brenda Reinhart. Sitting: Totte Niittyta, Jennifer Johnson, Wolf Frommer, Christopher Wilks, Daniel Yoo, Douglas Becker, Sakiko Okumoto, Gabi Fiene. Standing: Nakako Shibigaki, Angelica Vazquez, Nathan Gendron, Shauna Somerville, Christopher Somerville. Third row: Serry Koh, Devaki Bhaya, Julie Tacklind, Mamatha Hanumappa, Rachel Huntley, Kathi Bump, Joergen Persson. Fourth row: Laurent Zimmerli, Marta Perrocal-Lobo, Bi-Huei Hou, Chunxia Xu, Sue Thayer, Melanie Hilpert, Sam St. Clair. Fifth row, sitting on ledge: Matt Evans, Ida Lager, Sylvie LaLonde, Zhi-Yong Wang, Hartmut Foerster, Brandon Zoeckler. Sitting on steps: Doriann Moss, Karen Deuschle, Srini Gampala, Joshua Gendron, Stefan Bauer, Zheng-Hui He, Diane Chermak, Patti Poindexter, Kathryn Barton. Sitting on ledge: Jennifer Milne, Susan Cortinas, Christophe Tissier, Matthew Humphry, Ismael Villa, Ginger Brininstool, Steve Pollock, Wenqiang Tang. Top row standing: Marc Nishimura, Marcella Pott, Arthur Grossman, Hong Gu, Katica Ilic-Grubor, Nick Kaplinsky, Natalie Khuri, unidentified, Anne-Soisig Steunou, Stephan Eberhard, Raj Sandhu, Soo-Hwan Kim, Tae-Wuk Kim, Alex Paredez, Mary Smith, Glenn Ford, Yu Sun, Zhiping Deng, Jun-Xian He, Rene Wuttke.



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Daniel Yoo, *Programmer*
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Peifen Zhang, *Curator*
Daniel Zimardi, *Intern*³⁵
Brandon Zoeckler, *Assistant Curator*⁵²

¹From July 1, 2003²To August 31, 2003³From June 1, 2004⁴From January 2, 2004⁵From August 15, 2003⁶From September 1, 2003⁷From August 27, 2003⁸From January 16, 2004⁹From September 8, 2003¹⁰From May 1, 2004¹¹From February 1, 2004¹²To December 16, 2003¹³To July 31, 2003¹⁴From July 24, 2003¹⁵From January 18, 2004¹⁶From August 21, 2003¹⁷To August 1, 2003¹⁸From January 5, 2004¹⁹From August 1, 2003²⁰To March 31, 2004²¹From July 1, 2003²²To December 23, 2003²³To October 31, 2003²⁴From August 22, 2003, to February 28, 2004²⁵From March 22, 2004²⁶To July 29, 2003²⁷From March 4, 2004²⁸From February 23, 2004²⁹From November 1, 2003³⁰To September 15, 2003³¹From July 17, 2003, to April 30, 2004³²From September 23, 2003, to May 31, 2004³³From July 1, 2003, to August 31, 2003³⁴To October 6, 2003³⁵From June 8, 2004³⁶From August 19, 2003³⁷To August 8, 2003³⁸From June 16, 2004³⁹From July 1, 2003, to September 15, 2003⁴⁰To January 15, 2004⁴¹To August 22, 2003⁴²To August 15, 2003⁴³From September 24, 2003⁴⁴To July 31, 2003⁴⁵To March 19, 2004

⁴⁶To June 30, 2004
⁴⁷From May 3, 2004
⁴⁸To July 15, 2003
⁴⁹To August 31, 2003
⁵⁰From September 3, 2003
⁵¹From July 1, 2003, to December 31, 2003
⁵²From August 11, 2003

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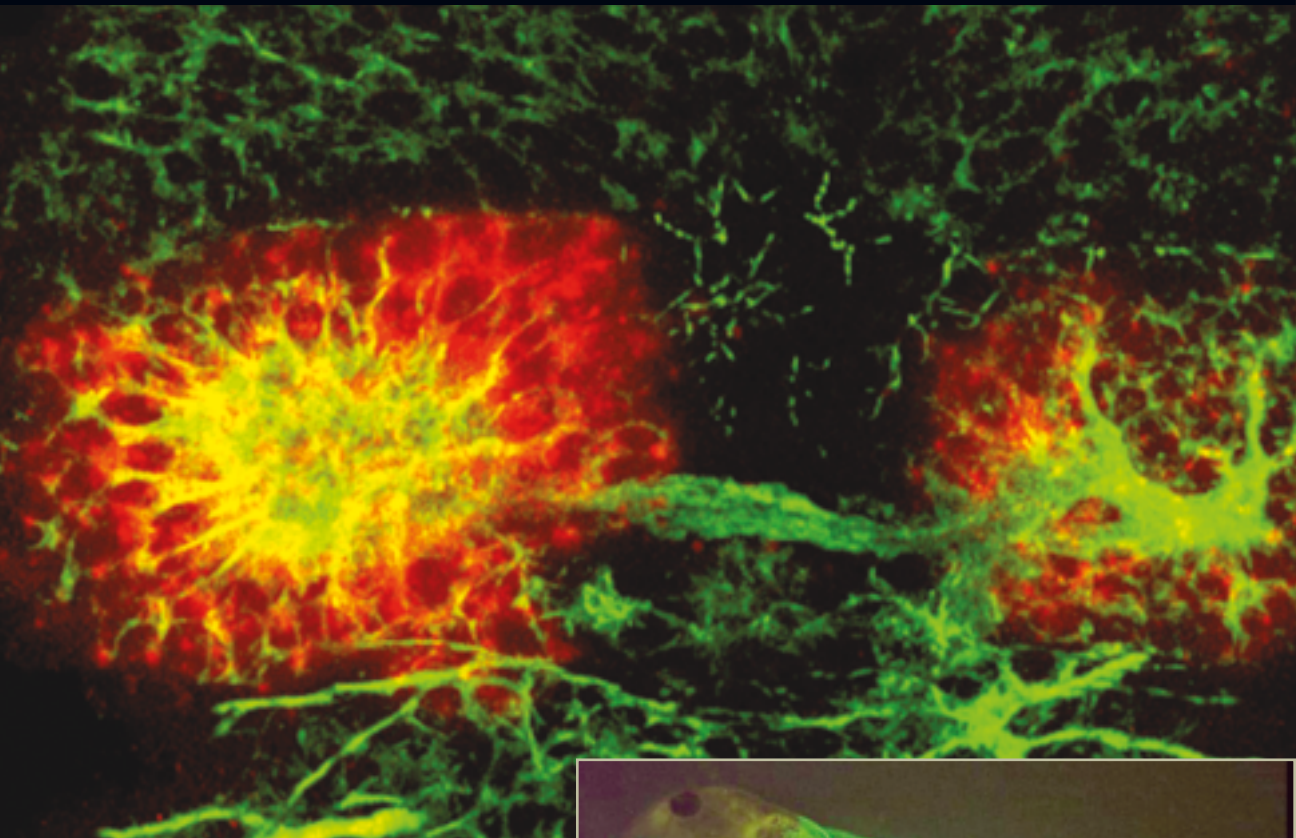
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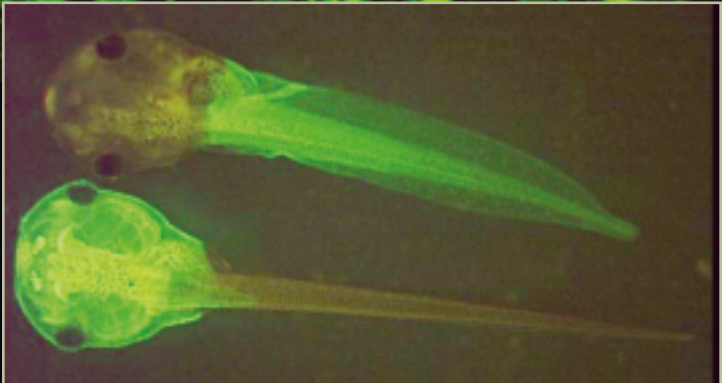
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Researchers at Carnegie's Department of Embryology are leaders in cellular, developmental, and genetic biology. The scientists use a variety of model organisms to understand key molecular processes within cells. This collection of images is a sampling of their investigations.



Marnie Halpern's laboratory uses the zebrafish to explore asymmetrical differences in the brain. Cells from the left and right sides, shown here, have different patterns of gene expression, indicated by the red and green areas. (Image courtesy Marnie Halpern.)



Xenopus laevis tadpoles are studied in Donald Brown's laboratory to determine how thyroid hormone signaling drives growth and development, particularly metamorphosis. These one-week-old tadpoles are half control and half transgenic for a gene encoding the green fluorescent protein. (Image courtesy Donald Brown.)

THE DIRECTOR'S REPORT:

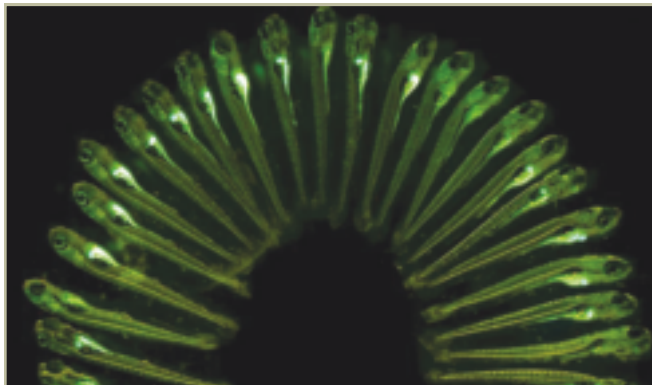
Exuberance and the Future of Biological Research

Biology is the deepest science. Today the Earth hosts millions of species of multicellular organisms, whose individuals may contain trillions of interacting cells comprising thousands of distinct cell types, arrayed in intricate three-dimensional patterns and directed by tens of thousands of differentially expressed genes. Now comes the complicated part: Unlike the fundamental entities of the physical sciences that follow simple laws, cells and their genes have been shaped by billions of years of shifting evolutionary pressures, ensuring that their behavior belies ordinary expectation. Current species and genomes represent only a snapshot in the continuum of now extinct forms, adapted to now extinct environments, stretching back to the first organized groupings of biomolecules on the young Earth. Consequently, each molecule's and organism's properties still partly reflect the obliterated history of countless ancient crises, beyond prediction, never to be revealed. In short, it is no exaggeration that the story of life on Earth comprises by far the most complex phenomenon known in the universe.

The theory-rich research style that is so powerful within the physical sciences and for characterizing biomolecules has routinely foundered on both the complexity and the evolutionary underpinnings of biological problems at the level of the cell. This deficiency is not a gap of a few odd orders of magnitude, bridgeable by new technology, as new immigrants from the physical sciences frequently imagine. Crossing the physics-biology gulf would require a molecular computer the size of the Earth's biosphere to churn for 3 billion years, in scant hope of duplicating the evolutionary computation whose final outputs are stored in the germline genomes that we observe today. However, despite seemingly insur-

perable obstacles, biological research has thrived. Successful biologists, whether former physicists or not, have learned to approach problems experimentally, to use genes as their fundamental particles, and to thereby coax organisms into revealing the molecules and mechanisms evolution selected for particular purposes.

This style of biological research meshes synergistically with an American system that gives autonomy and resources to relatively young investigators. During the last 100 years, independent scientists, working with small groups of trainees, have ushered genetics through four successive "revolutionary" eras: classical genetics, molecular biology, molecular cloning, and now genomics. The Carnegie Institution, practicing American-style biological research in one of its purest forms, has played a disproportionate role in each of these eras through its support of Thomas Hunt Morgan, at



Steven Farber uses the zebrafish to study various biochemical processes in live fish, especially those related to lipids. Some of the sibling fish shown contain a newly induced mutation that blocks normal lipid uptake (green). Sibs that inherited two copies of the mutant gene contain little or no lipid. (Image courtesy Steven Farber.)

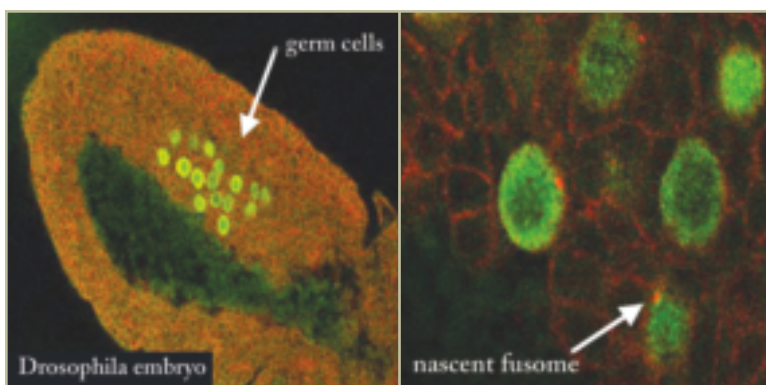
its Department of Genetics, and since about 1970 here at the Department of Embryology. The very concept of today's "reverse genetics" was born in this department, and fundamental technologies for manipulating genes, used daily in genomics research around the world, were developed here. Recently, the genome projects and industrial biotechnology that spurred the genomics revolution demonstrated the additional value of a larger scale and a more industrial style of biological research and development. These events raise questions about the appropriate style and scale of future research at the Department of Embryology.

In considering our future, a little history is helpful. Overcoming the seemingly insurmountable scientific challenges inherent in biological research is thrilling. Perhaps this is why major biological advances have often engendered a kind of irrational exuberance that has blinded even leading researchers to the immensity of what remains. In the 1960s, after discovering the first molecular gene regulatory circuit using the intestinal bacterium *E. coli*, Jacques Monod, famously (but later to his regret) remarked that "*E. coli* is like an elephant." Other early molecular biologists convinced themselves that the scientific journey itself was drawing to a close, or that the only remaining problems of significance lay within the highest levels of neuroscience. Following the advent of molecular cloning, some scientists seriously believed it would be possible to easily transfer major functional capabilities, such as nitrogen fixation, between species. Others expected we would soon engineer fantastic new creatures, such as "alligators with fur," to quote a "conservative prediction" from a typical newspaper account.

Today's genomic era, so reminiscent of the period following the molecular biology revolution, has likewise generated considerable exuberance. The success of large-scale DNA sequencing has led to a credulous enthusiasm among influential leaders for science projects of a scale larger than the traditional research group. Among the most exu-

berant, biology is seen as finally ready for physics-style research, and institutes to promote such collaborations have appeared on the campuses of major universities. Some even dream that big projects can replace the research of small independent investigators, using massive datasets collected by robots that can be computationally analyzed to build an abstract theory of the cell. New immigrants from the physical sciences, driven from their fields by woefully inadequate public funding and lacking personal knowledge and experience of biological reality, are naturally inclined to believe this chimerical vision.

NIH leaders have also been strongly influenced by genomic exuberance. They proclaim that we now possess sufficient basic knowledge to justify an increased focus on applications. Privately, the inevitable concomitant decrease in basic research is considered acceptable, because independent basic scientists are seen as increasingly occupied with "details" more efficiently analyzed by interdisciplinary collaborations and high-throughput centers. Because of a confluence of factors, NIH funding of investigator-initiated basic research has plummeted, forcing beginning biologists who had hoped to pursue their own ideas to contemplate subordinate positions, where new ideas have little chance to arise and flourish. Current generations of trainees anxiously observe the difficulties of young



The fruit fly, *Drosophila*, is studied in several labs at the department. Allan Spradling uses the genetically favorable creature for his research into the molecular mechanisms of egg production. Here the germ cell precursors of eggs within a *Drosophila* embryo have been labeled green (left) to reveal a unique small organelle they contain known as the fusome (right, red). (Image courtesy Allan Spradling.)

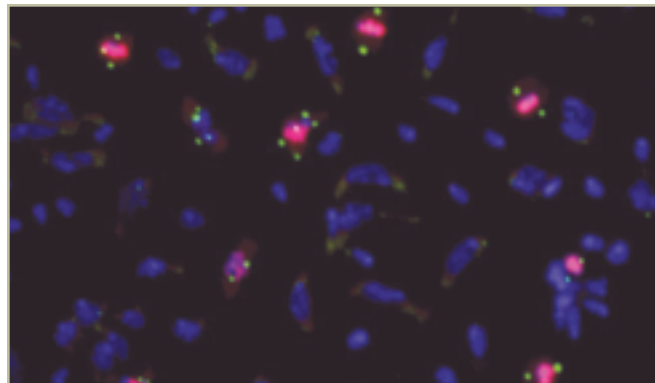
faculty members and the outsized enthusiasm for big projects, and wonder where their science and their careers are headed. Unchecked, these trends threaten the fundamental engine of biological discovery, American style.

Has biology entered a truly new epoch—the “postgenomic” era, that justifies a significant restructuring of our highly successful research enterprise? Well, knowledge (and especially data) has increased, just as it did after the advent of classical genetics, molecular biology, or recombinant DNA. Moreover, we now enjoy permanent (hopefully) public information resources such as major genome and bioinformatic projects as well as new reagents and technologies available for purchase from the private sector. However, these welcome improvements should not obscure the immense problems and challenges of studying multicellular organisms. “Postgenomic” technology is quantitatively better, but as discussed below it remains qualitatively inadequate to address the key problems of elephants in any straightforward or scalable manner. Consequently we should be wary of exuberantly overestimating the power of current genomic technology, lest this skew research priorities, misdirect scarce resources, and perhaps most significantly, discourage the trainees and young scientists who will be needed to reap the immense promise of the genomic era.

In my view, the excessively exuberant view of where biology currently stands comes from a failure to appreciate the severe remaining limitations of analyzing multicellular organisms. I once participated in an NIH-sponsored workshop on how to discover the function of all the genes in the human genome. It was organized in three sections: DNA, RNA, and protein. These are obviously important subjects, greatly impacted by genomics. Entirely lacking, however, were the many additional levels of biological organization above the level of the proteome, which remain crucial for understanding gene action in multicellular organisms (human and otherwise). In fact, today’s genomics could more accurately be termed “single cell genomics.” Its methods and concerns remain focused on individual cells, like the microorganisms, cultured animal cells, and viruses

utilized by traditional molecular biologists. The sciences of multicellular biology—anatomy, physiology, developmental biology, neurobiology, evolutionary biology, etc.—continue to be politely ignored. In effect, exuberant single-cell genomicists have been saying, “Yeast is like an elephant.”

In fact, we do not yet possess the technical means to undertake many of the critical problems of multicellular organisms on a big-project scale. A truly multicellular genomics would require, at a minimum, the development of a new fundamental capability I call “anatomical genomics.” Anatomical genomics would provide methods to rapidly map an animal’s structure cell by cell and record it electronically. Current microscopic and histological methods cannot position most of the (possibly trillions) of cells in animal tissues, outline their individual shapes, or subdivide them into cell types. This information needs to be obtained rapidly and dynamically. Structures change quickly with time, and one frequently needs to know how cellular growth, cell shape change, cell division, and cell migration transform one anatomical stage into another. Without such information one cannot fully describe, much less understand, how tissues develop, function, or become diseased, or deduce the roles particular genes play in these processes. Those who work on multicellular organisms have learned from experience that some of the most



When animal cells divide, they depend on activities in an area of the cell near the nucleus called the centrosome. The Terence Murphy lab studies the pathway that governs centrosome duplication. They found that a complex called SCF^{slimb} is important to the process. When SCF^{slimb} is functioning, it prevents growing cells (red) from accumulating more than two centrosomes (green). (Image courtesy Terence Murphy.)

important insights into gene function come from knowledge gained at the cellular level and not just from studies of DNA, RNA, and protein. Unlike premature theorizing, learning how to systematically determine and electronically display cellular anatomy are well-defined problems that could productively challenge any physical scientist interested in having a major impact on biology.

Systematic cellular anatomy is an inherently genomic science. Cell types, the key to understanding tissues, are ultimately defined by gene expression programs. So in principle, to find all cell types one needs to map the expression of all genes throughout all the cellular anatomy during all developmental stages and environmental states. Even in model organisms and humans, only a handful of abundantly expressed genes have been studied, and mostly at lower than single-cell resolution. Consequently, it should come as no surprise that many, perhaps most, cell types have yet to be discovered. I believe, in fact, that a whole level of biological organization has largely been overlooked—a level larger than the single cell but smaller than a full-blown tissue. It consists of small, highly organized, interactive, supracellular modules made up of a few cell types. Only a small number of these units have been recognized by classical anatomists, and have been given such names as “crypts,” “islets,” “follicles,” “niches,” “cysts,” etc. Such units likely constitute the basic building blocks of tissues, and operate using mechanisms and genes conserved over long evolutionary periods. Thus, the cellular anatomy genome project not only represents a fundamental prerequisite for any systematic analysis of metazoan gene function but also promises to provide profound new insights into the structure and function of animal tissues.

Current visions of “big” biology also suffer from an even more fundamental flaw. The process of determining genomic DNA sequences is thriving, but fundamental difficulties remain at every step above and below the primary sequence level. Despite years of effort, it is not possible to read much biological information from genomic sequences. How RNA production is specified, which RNAs are made into protein, and which proteins are further

modified or turned over can only be determined by experiment for each cell, in each organism, in each situation. The fact is, we have not yet discovered many of the basic biological mechanisms that govern the cell, much less how cells interact. The fact that RNA interference, a universal, fundamental process in which small double-stranded RNAs specifically target and regulate gene expression, was unknown just a few years ago should give pause to those who argue that small labs are now enmeshed in biological details. Many more “RNAi’s” remain to be discovered at every level of cellular function. As with RNAi, these truly novel mechanisms are unlikely to be uncovered by large projects, by data-gathering exercises, or by road maps. They can only be brought to light by creative individuals following their own instincts. History teaches us that some of the most important future medical applications will also come from such discoveries.

Consequently, the situation facing our department today is quite different from the dilemma that is sometimes portrayed. Our small size, diverse expertise, independent resources, and lack of an overarching mission remain powerful advantages. We have access to the fruits of big biology without the stultifying side effects of large organizations. We are strategically located on the Johns Hopkins campus near a diverse community of biologists as well as physicists, computer scientists, and engineers. However, we have the freedom to let interdisciplinary collaborations grow naturally out of shared interests and novel ideas rather than institutional necessity. We believe that the scientific opportunities have never been better for an independent researcher within such an environment.

The task facing our staff remains that of finding a territory within the vast frontier of biology where current ideas and assumptions, or the lack thereof, are holding back progress. Circumventing such roadblocks has diverse, unpredictable side benefits throughout many areas of research. This type of inquiry differs enormously from filling in the details of a process already fully understood in rough outline (which is not our goal), although we recognize that when a project starts, the distinction exists mainly in the intuition and imagination of



Members of the Department of Embryology staff are shown. First row (from left): Allan Spradling, Bill Kupiec, Dianne Williams, Chen-Ming Fan, Mike Buszczak, SarahScott Brett, David Martinelli, Jinzhe Mao. Second row: Jovita Diaz, Allison Pinder, Aja Campbell, Ben Ohlstein, Lori Orosco. Third row: Ella Jackson, Rejeanne Juste, Tina Tootle, Nicole Crnkovich, Lea Fortuno, Elcin Unal, Judy Yanowitz, Jen Anderson, Alex Bortvin, Zheng-an Wu, Bishu Das, Kiran Santhakumar, Liquan Cai. Fourth row: Ji-Long Liu, Marnie Halpern, Christoph Lepper, Margaret Hoang, Christian Broesamle, Mike Welch, Rachel Cox, Eva DeCotto, Terence Murphy, Cynthia Wagner, Carol Davenport, Tara Hardiman, Catherine Huang, Chris Edwards, Pat Cammon, Eugenia Dikovskaia, Mahmud Siddiqi, Christine Norman, Ellen Cammon, Milena Vuica, Mark Milutinovich, Joseph Gall, Doug Koshland, Don Brown, Hong-Guo Yu.



the investigator. Our staff's predilection for problems revolving around chromosomes, germ cells, and developmental signals results from this pattern. Additionally, Carnegie faculty continue to show a willingness to change directions, and to recognize influxes of new workers to their research topics as true signs of success. There is often a lot of traffic backed up behind a roadblock.

Finally, we remain committed to advancing the techniques for studying multicellular organisms available to the research community. Just as there are many more RNAi's left, there are more revolutions remaining in the history of genetics. We are just beginning to acquire the tools to understand biological levels above the individual cell. Most of what goes on during the development, environmental interaction, and evolution of complex organisms remains as closed to us as in Monod's day. The next era after genomics, an era that will open up the study of multicellular life, can only become reality from the efforts of those who remain dissatisfied with the status quo, and who dream of a better and more powerful biological science.

Our department continues to house many such individuals. My group has become increasingly interested in the "cellular anatomy" genome project as it applies to *Drosophila*. We recognize that the technology, even of the favored "model organisms" such as worms, flies, fish, frogs, and mice, is still mired at an early stage. Far more capabilities and resources will be needed to accelerate our analysis of the most pressing biological frontiers. The development of such technology seems well justified, because for understanding the development and physiology of metazoans, "Model organisms are truly like an elephant." Of course those currently in favor will not ultimately be enough. Many additional model organisms, with equivalent technologies, strategically placed throughout phylogenetic space will be required to probe the pathways that shape animal evolution and to decipher the forces that adapt organisms for specialized environments and life strategies. Biology is the deepest science; its future, not just its present accomplishments, gives us much to be exuberant about.

—Allan C. Spradling

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¹⁴To October 30, 2003
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¹⁶From May 24, 2004
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¹⁸From June 23, 2004
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²³To June 24, 2004
²⁴To August 14, 2003
²⁵To June 28, 2004
²⁶To March 3, 2004
²⁷From August 5, 2003
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THE DIRECTOR'S REPORT:

Investigation, Research, and Discovery

"IT IS PROPOSED TO FOUND IN THE CITY OF WASHINGTON,
AN INSTITUTION WHICH...SHALL IN THE BROADEST AND MOST LIBERAL
MANNER ENCOURAGE INVESTIGATION, RESEARCH, AND DISCOVERY..."

—*Andrew Carnegie (1902)*¹

When Andrew Carnegie gave his initial gift establishing the Carnegie Institution of Washington, his vision for promoting science was "to discover the exceptional" individual and to provide an opportunity for that scientist to devote his or her attention to the pursuit of work for which he or she "seems specially designed." The archetype of that vision, by tradition, is the bench scientist who alone or perhaps with a few close collaborators conceives and carries out the experiments needed to advance a particular line of scientific inquiry. Among the leaders of the institution throughout its history, however, have been supremely gifted administrators of large scientific endeavors—epitomized by Vannevar Bush, who while president of the Carnegie Institution ably led the nation's Office of Scientific Research and Development during World War II. As the global scientific enterprise has grown in size and complexity, the question of the scale of scientific programs appropriate to the institution has been a natural topic for continued discussion. Most such deliberations have reinforced the traditional view of Carnegie's vision—that the role of the institution is to invest in the creative individual. Merle Tuve, director of the Department of Terrestrial Magnetism (DTM) from 1946 to 1966, was an outspoken advocate of such a position. He wrote that "no array of feedback arguments will convince very many of us that the real germ of new knowledge is the product of team activity or the result of large-scale instruments or implements...

I believe we should take the firm position on the point that the support of true basic research is the support of ideas and that this always means the support of a creative investigator."²

There are nonetheless topics of great scientific interest that require access to facilities or instrumentation beyond the means of a single laboratory or department. One cannot study most processes in or beneath the Earth's oceans without oceanographic ships, one cannot carry out most frontier projects in observational astronomy without modern telescopes, and one cannot investigate the details of the planets of our solar system without spacecraft. For the past five and a half years I have served as the Principal Investigator for a spacecraft mission to study the planet Mercury. That spacecraft—MERcury Surface, Space ENvironment, GEOchemistry, and Ranging, or MESSENGER—was launched in August 2004 and after a long and circuitous route through the inner solar system will become, in March 2011, the first probe to orbit Mercury. Is the leadership of a spacecraft mission of exploration—an effort that surely qualifies as a large-scale "product of team activity"—consistent with the expressed intent of Andrew Carnegie and

¹ Andrew Carnegie, Deed of Trust, 1902, Year Book no. 1, p. xiii (Washington, D.C.: Carnegie Institution of Washington, 1903).

² Merle A. Tuve, "Is science too big for the scientist?" *Saturday Review* 62, no. 23, pp. 49-52, June 6, 1959.

the resolute opinion of Merle Tuve that the focus of our institution should be on the creative investigator? I believe that it is.

The innermost planet has been visited by only a single spacecraft. *Mariner 10* flew by Mercury three times in 1974 and 1975. Each flyby was separated by two Mercury “years”—two revolutions of Mercury about the Sun. Mercury is in a rotational state unique in the solar system, in that the planet’s spin period is exactly two-thirds of the rotational period. As a consequence the solar day on Mercury—the time between successive passages of the Sun overhead—is equal to two Mercury years. *Mariner 10* therefore saw the same side of Mercury lit by the Sun during each of its three close encounters, and more than half of Mercury was never imaged. The images of the surface that *Mariner 10* did obtain stimulated arguments about the planet’s geological history that continue to the present, and other discoveries by *Mariner 10* raised many questions still not answered.

Even before the *Mariner 10* mission, it was known that Mercury is unusually dense. After correcting

for the effects of self-compression by interior pressure, the “uncompressed” density of the material inside Mercury is substantially higher than that of any of the other planets. Because Mercury, like the other inner planets, is composed of rock and metal, the high density implies that the mass fraction of metal occupying a central core in Mercury is at least 60%, a fraction twice as high as that for the Earth (Fig. 1). Mercury’s high metal fraction must date from early in solar system history when the inner planets were assembled from material within the nebula of dust and gas that surrounded the young Sun. One hypothesis is that the material of the innermost nebula, from which Mercury was later predominantly accreted, was enriched in metal because the lighter silicate grains were preferentially slowed by interaction with the nebular gas and tended to fall into the Sun. Another hypothesis is that after Mercury accreted to full planetary size and a central metal core differentiated from a silicate shell, the silicate fraction was partially vaporized by a high-temperature nebula and the vapor was driven off by a strong solar wind. A third hypothesis—championed by DTM’s George Wetherill—is that after Mercury accreted

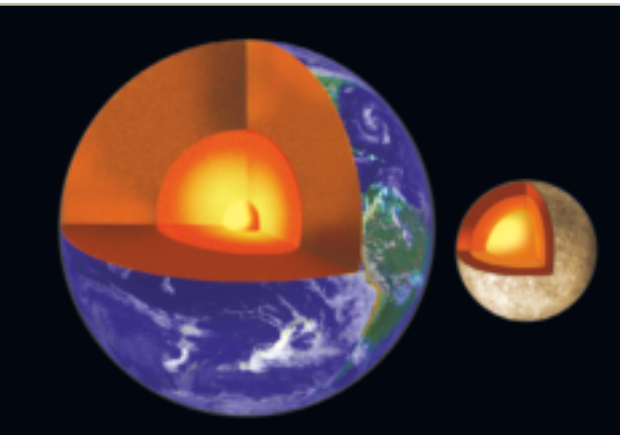


Fig. 1. On the basis of its bulk density, Mercury must have a central core consisting mostly of iron metal and occupying a fraction of the planetary interior much larger than that for Earth’s core (left). Earth has a solid inner core and a fluid outer core, shown to approximate scale; Earth’s magnetic field is sustained by a hydromagnetic dynamo in the outer core. The nature of Mercury’s core and the origin of the planet’s magnetic field remain to be determined. (Image courtesy NASA and The Johns Hopkins Applied Physics Laboratory.)

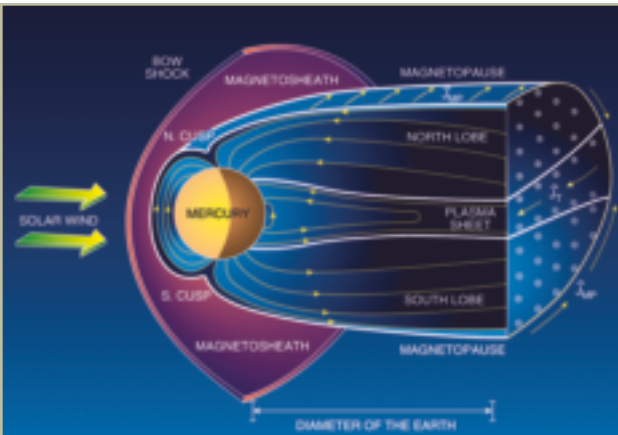


Fig. 2. Observations by *Mariner 10* and extrapolations from spacecraft measurements near the Earth suggest that the magnetosphere of Mercury is a miniature version of the Earth’s magnetosphere generated by the interaction of the Earth’s internal magnetic field with the solar wind. Many details of Mercury’s magnetic field and magnetosphere are not understood, however, in large part because of the limited sampling by *Mariner 10*. (Figure courtesy James A. Slavin, NASA Goddard Space Flight Center.)

and differentiated core from mantle, the planet was the target of a giant impact that stripped off and ejected much of the outer silicate fraction. These three hypotheses, which differ strongly in their implications for how the inner planets came to differ in bulk composition, are testable because they predict different outcomes for the major-element chemistry of the silicate fraction of the planet.

Mariner 10 carried no chemical remote sensing instruments, and ground-based efforts to deduce compositional information about Mercury's surface from the identification of mineral absorption bands in reflected visible and infrared radiation have had only limited success. Sorting out how Mercury ended up a dominantly iron planet requires chemical remote sensing from an orbiting spacecraft.

One of the major discoveries of *Mariner 10* was that Mercury has an internal magnetic field. This was a surprising finding, because a planet as small as Mercury should have cooled over its lifetime to a greater extent than Earth. Earth's magnetic field is known to arise through the dynamo action of convective motions in its fluid metal core, and numerical models of interior cooling predict that a pure iron core in Mercury would have fully solidified by now. The field detected by *Mariner 10* appears to be predominantly dipolar, like Earth's field, but the dipole moment is smaller by a factor of about 10^3 . An Earth-like hydromagnetic dynamo in a fluid outer core is only one of several ideas postulated to account for Mercury's magnetism. A fossil field in Mercury's crust remaining from an earlier era when a core dynamo was active is another possibility, and more exotic dynamos (e.g., thermoelectric currents driven by temperature variations at the top of a metal core with a bumpy outer boundary) have also been suggested. These hypotheses can be distinguished because they predict different geometries for the present planetary field, and magnetic field measurements made from an orbiting spacecraft can separate internal and external fields and map the internal field. Mercury's magnetosphere—the envelope of space dominated by the planetary field and defined by the interaction of that field with the solar wind plasma streaming from the Sun—is the most similar to Earth's magnetosphere among the planets, but with important differences (Fig. 2).

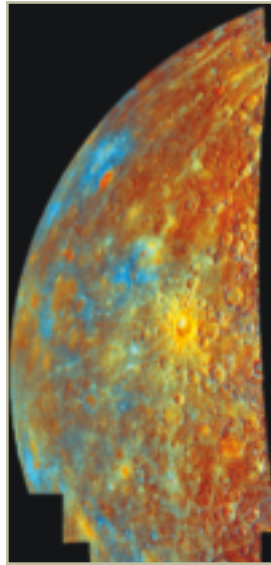


Fig. 3. *Mariner 10* images of Mercury were obtained with three color filters. This mosaic, with false colors selected to emphasize spectral variations with chemistry and mineralogy seen on the Moon, illustrates that geological units on Mercury can be distinguished on the basis of color and that information on mineralogy is derivable from surface spectral reflectance measurements. (Image courtesy Mark Robinson, Northwestern University.)

The solar wind fields are stronger closer to the Sun; Mercury occupies a much larger fractional volume of its magnetosphere because of its weaker internal field; and Mercury lacks an ionosphere, the site of important current systems in Earth's magnetosphere. Mercury's magnetosphere is therefore an important laboratory for generalizing our understanding of Earth's space environment.

The geological history of Mercury has been deduced from the images taken by *Mariner 10*, but there are many unanswered questions. Mercury's surface consists primarily of heavily cratered and smooth terrains (Fig. 3) that are at least superficially similar in morphology and relative stratigraphic relationship to the highlands and geologically younger maria, respectively, on the Moon. Whereas the lunar maria are known to consist of basaltic lava flows on the basis of samples returned by the Apollo missions and orbital images of frozen lava flow fronts in several maria, the smooth plains on Mercury are higher in albedo (i.e., brighter in reflected light) than the lunar maria and no volcanic features can be seen in the relatively coarse-resolution *Mariner 10* images. The role of volcanism in Mercury's history is therefore an open issue. From the standpoint of large-scale deformation, Mercury shows evidence for an

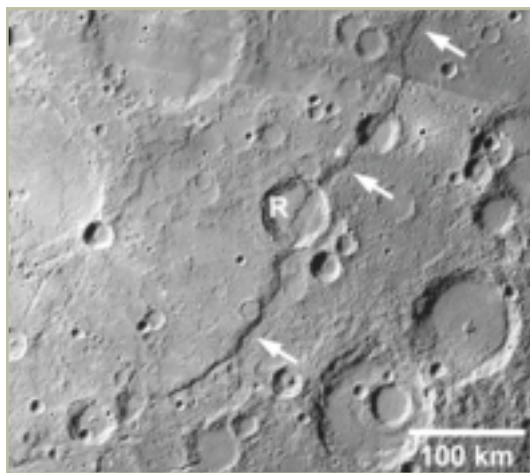


Fig. 4. The longest known lobate scarp on Mercury is Discovery Rupes, shown in this *Mariner 10* image mosaic. The scarp is 550 km long and displays 1 km or more of topographic relief. Arrows denote the approximate direction of underthrusting of the crustal block to the right beneath the block to the left. The crater Rameau (R), transected by the scarp, is 60 km in diameter. (Image courtesy Mark Robinson, Northwestern University.)

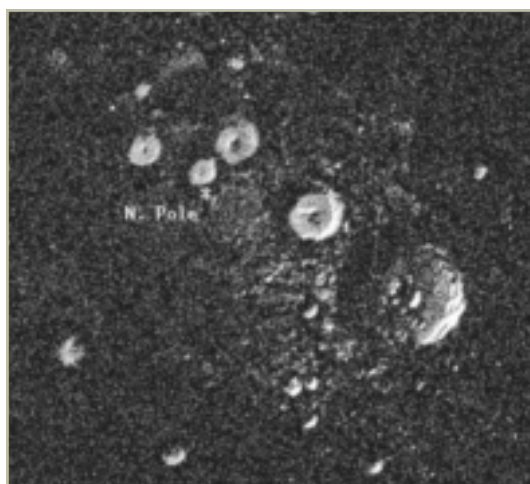


Fig. 5. This radar image of the north polar region of Mercury, obtained at the Arecibo Observatory in 1999, demonstrates that Mercury's radar-bright polar deposits lie within the floors of large impact craters. The radar direction is from the upper left, the resolution is 1.5 km, and the image is shown in polar projection. (Image courtesy John Harmon, Cornell University.)

interesting history. The most prominent deformational features are the lobate scarps (Fig. 4), thought to be the surface expression of large thrust faults produced by horizontal shortening of the crust. The apparently random orientations of these scarps on all terrain types has led to the interpretation that they are the product of global contraction—a shrinkage of the planet as the interior cooled and the core solidified. Global shrinkage was at one time suggested as an explanation for the formation of mountain systems on Earth, but that idea was discarded with the acceptance of plate convergence at subduction zones. Mercury may be the one planet where a record of such shrinkage is preserved. A critical test of that conclusion will be possible when images are taken of the hemisphere that *Mariner 10* did not view.

Mariner 10 detected the presence of hydrogen, helium, and oxygen in Mercury's tenuous atmosphere. Ground-based spectroscopic observations led to the discovery of additional species, including sodium, potassium, and calcium. Most of these constituents are too abundant to be derived from the solar wind, and their atmospheric lifetimes are much shorter than the age of the planet, so there must be steady sources at the planetary surface. The specific processes controlling the sources and sinks of atmospheric components are not well known, however. Key information from an orbiting spacecraft that would help to discriminate among competing hypotheses are the detection of additional species and the monitoring of atmospheric properties as functions of time of day, solar distance, and level of solar activity. One or more additional volatile species appear to be present at the surface near the planetary poles. Ground-based radar imaging of Mercury led to the discovery in 1991 of radar-bright polar deposits localized within the floors of near-polar impact craters (Fig. 5). The deposits have radar reflectivities and polarization characteristics that are well matched by water ice, although other materials have also been suggested. Ices are stable for billions of years in such areas because Mercury's obliquity (the tilt of its spin axis from the normal to the orbital plane) is nearly zero and the floors of near-polar craters are in permanent shadow and consequently very cold.

Remote sensing measurements from an orbiting spacecraft are needed to confirm the composition of these trapped volatiles.

Given the broad sweep of issues addressable with a Mercury orbiter, why did 30 years pass between the first Mercury flyby of *Mariner 10* and the launch of the next mission to the innermost planet? The answer to this question has several parts. After *Mariner 10*'s discoveries, there was widespread interest in a Mercury orbiter mission, but it was thought that conventional propulsion systems could not be used to inject a spacecraft into Mercury orbit because the required change in velocity was too large. In the mid-1980s multiple gravity-assist trajectories were discovered that could achieve Mercury orbit insertion with existing propulsion systems, but the 1980s were a difficult era in the history of planetary mission launches. NASA had adopted the policy that the Space Shuttle would be the sole launch vehicle for its missions. At the same time, the planetary exploration program was emphasizing large, complex, and costly spacecraft, which for budgetary reasons tended to be launched infrequently. The *Challenger* disaster in 1986 shut down NASA's launch capability and created a queue of planetary missions awaiting flight. By 1989, when flagship missions to Jupiter and Venus were launched, 11 years had passed since the previous U.S. planetary mission had left Earth. In the early 1990s, NASA reexamined its approach to planetary exploration, and Wesley Huntress—now the director of the Geophysical Laboratory but at that time the NASA Associate Administrator for Space Science—initiated the Discovery Program.

The Discovery Program is a partnership between NASA and the planetary science community whereby mission opportunities are regularly competed. Limits are set on total mission cost, development time, and launch vehicle, but a proposing team is free to offer any mission concept that satisfies those limits. Review panels then recommend for selection the mission proposals that offer compelling scientific return but are at the same time technically and financially feasible. Mercury was the target of a number of early unsuccessful proposals to the Discovery Program, but the MES-

SENGER mission concept was born when engineers and space scientists at The Johns Hopkins University Applied Physics Laboratory (APL) came up with mission and spacecraft designs that looked practicable. In 1996 APL approached me about serving as Principal Investigator for a Discovery Program proposal, and after a couple of early discussions I agreed. We assembled a team of scientific investigators, and we selected a set of payload instruments that could make all of the global measurements discussed above. Our proposal was selected for further study, but our second-round effort in 1997 was deemed too risky by NASA, in large part because of concern with the ability of the spacecraft to survive the harsh thermal environment at Mercury. APL carried out an



Fig. 6. The complex process of assembling and testing the MESSENGER spacecraft and mating it to its launch vehicle extended over a year and a half. Shown is the spacecraft on July 14, 2004, after it was attached to the payload assist module of the Delta II third stage at Astrotech Space Operations in Titusville, Florida. The two flat, reflective panels are the solar arrays stowed in their launch positions. (Image courtesy NASA and The Johns Hopkins University Applied Physics Laboratory.)

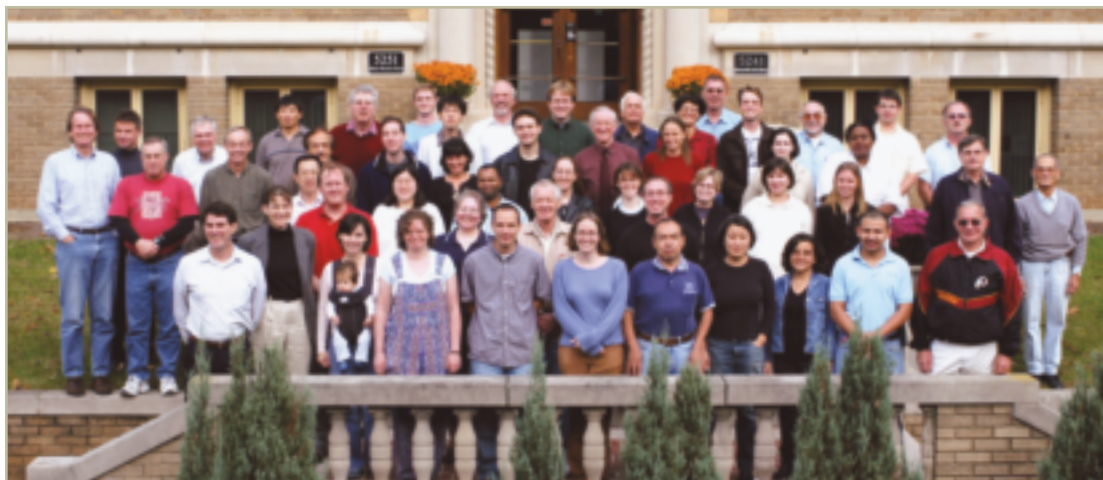


Fig. 7. Members of the Department of Terrestrial Magnetism staff are shown on November 3, 2004. First row (from left): Timothy Mock, Lucy and Charles Flesch, Linda Warren, Brian Savage, Katherine Kelley, Pablo Esparza, Aki Roberge, Mercedes López-Morales, Adelio Contrera, and Roy Dingus. Second row: Susan Webb, Erik Hauri, Sandra Keiser, Alan Linde, and Richard Carlson. Third row: Alan Boss, Nelson McWhorter, Steven Shirey, Kevin Wang, Hannah Jang-Condell, Maceo Bacote, Lindsey Bruesch, Alexis Clements, Jennifer Snyder, Oksana Skass, Maud Boyet, Terry Stahl, and Pedro Roa. Fourth row: Gotthard Sági-Szabó, John Graham, Fouad Tera, Scott Sheppard, Janice Dunlap, John Chambers, Sean Solomon, Maria Schönbachler, Sara Seager, and Brenda Eades. Fifth row: Jianhua Wang, Kevin Burke, Jay Bartlett, Taka'aki Taira, Paul Silver, Henner Busemann, Selwyn Sacks, Daniela Power, Gary Bors, Charles Hargrove, Georg Bartels, Brian Schleigh, and Bill Key.



extensive testing of critical spacecraft components under high-temperature vacuum conditions, and we reproposed in 1998. We were again selected for a second phase of study, and after a thorough second review MESSENGER was selected for flight in July 1999. Within a week of selection, Congress had cut MESSENGER and several other missions from the NASA budget then under consideration, but by the passage of the final appropriations bill that year MESSENGER had been restored.

Between mission selection and launch were five event-filled years. We saw multiple changes in programmatic management at NASA and heightened concern for mission risk as a number of other robotic and piloted missions suffered losses. The MESSENGER team struggled with changes in project management and engineering subsystem leadership, late delivery of key subsystems and instruments, multiple failures of critical electronic components, consequent schedule delays, and two postponements of launch opportunities. A robust and thoroughly tested spacecraft nonetheless was delivered, mated to its launch vehicle (Fig. 6), and successfully sent on its multiyear journey toward Mercury.

The MESSENGER mission carries two notes of irony. The first is that one of the principal objectives of the mission—to understand Mercury's magnetic field and its relationship to the Earth's magnetic field—runs counter to the fact that terrestrial magnetism has not been a major focus of research at DTM for nearly half a century.

The second irony is that the organization that designed and built the MESSENGER spacecraft and is now managing the mission is APL, established by Merle Tuve during World War II as an off-campus laboratory to complete the development of the antiaircraft proximity fuze. Notwithstanding Tuve's admonition that a large-scale "product of team activity" is rarely if ever a "germ of new knowledge," the members of the MESSENGER team at the institution that Tuve began are working hard to ensure that the spacecraft successfully carries out its full mission. Given its broad objectives, MESSENGER surely fits Andrew Carnegie's intention that this institution "encourage investigation, research, and discovery."

—Sean C. Solomon

July 1, 2003 – June 30, 2004

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⁹To September 30, 2003

¹⁰To December 31, 2003

¹¹From November 7, 2003

¹²From August 25, 2003

¹³To March 31, 2004

¹⁴From June 23, 2004

¹⁵From October 1, 2003

¹⁶Joint appointment with GL

¹⁷From October 1, 2003

¹⁸To December 31, 2003

¹⁹To January 23, 2004

²⁰From February 9, 2004

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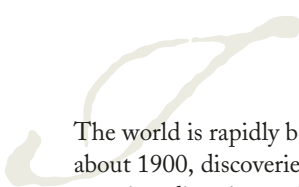
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THE DIRECTOR'S REPORT



The world is rapidly becoming smaller. Prior to about 1900, discoveries emphasized the Earth's vast size, diversity, and complexity, which made the world seem big. Scientists assembled giant catalogs of the rocks of the Himalayas and the birds of New Guinea, but they did not understand the processes that led to their diversity and relationships. The 20th century witnessed an explosion of new knowledge about the underlying mechanisms governing these observations, ranging from evolution by natural selection to plate tectonics. These advances provided a framework for understanding the structure, function, and origin of the natural world. And this framework has become a major force shrinking the world, as it increasingly allows explanations of how the vast diversity of organisms, structures, and processes are linked.

Science is now embarking on a broad series of ventures that will shrink the world even further. If the 20th century was the age of mechanism, the 21st will almost certainly be the age of integration. The combination of greatly expanded observations and knowledge about the workings of individual processes is creating the opportunity to discover mechanisms that operate across many levels of organization. This trend is occurring across the sciences, but especially in biology. One example is in the flowering of genomics, a field based on molecular tools that link the function of genes and whole organisms. Another is in neurobiology, which has moved from the study of neurons to the study of nervous systems. In ecology, the era of integration

is developing along many paths. All of these, however, are characterized by an emphasis on understanding how interactions among the parts of the Earth system—ecosystems, the physical earth, and people—shape its structure, function, and future. The breakthroughs in the field of ecology in the 21st century will come less from details about the workings of parts of the system than from understanding the connections.

The Department of Global Ecology (DGE), founded on July 1, 2002, is at the forefront of integration in ecology. Linking concepts and approaches from biology, atmospheric science, soil science, hydrology, and even the social sciences, members of the department are developing new perspectives on ecosystems and the ways they function. Ours is basic research, but it is research closely related to applied questions. In the face of human actions leading to land-use change, climate change, introductions of non-native plants and animals, and losses of native species, an understanding of the processes that underlie ecosystem structure and function is a critical prerequisite for intelligent decisions about managing the future.

Throughout the department's first years the three founding faculty members—Greg Asner, Joe Berry, and I—have worked on diverse problems, ranging from local to global in scale, and in locations as varied as our new lab in California to the deserts of Arizona and the forests of Brazil (Fig. 1). In addition to doing research, we were active as



Fig. 1. Much of the work of the department involves high-tech instruments or complicated computer models. A large fraction, however, involves getting to remote field sites for simple measurements. Here, Greg Asner employs appropriate technology to access field sites in the Brazilian Cerrado, a dry forest. (Image courtesy Gabriela Nardoto.)

editors and synthesizers. Greg, along with Ruth DeFries (University of Maryland) and Richard Houghton (Woods Hole Research Center) edited a major new book on ecosystems and land-use change. Mike Raupach (CSIRO Australia) and I edited a new synthesis on the global carbon cycle. All of our activities were marked by an emphasis on integration, on using new concepts and tools to expand the domain of feasible investigation.

One of the main thrusts in the research over the last year was to extend analytical techniques to operate over larger areas. This step is critical to accurately quantifying large-scale processes, which are too often estimated from spot measurements and questionable scaling algorithms. Joe's lab has taken a lead in scaling the technology for measuring chlorophyll fluorescence from the level of a single leaf to the scale of the canopy. When leaves of a plant absorb light, they reemit a small fraction as fluorescence, which emanates from chlorophyll, the key pigment of photosynthesis. Chlorophyll fluoresces at a characteristic wavelength that is longer (redder) than the light it

absorbs. Variations in the fraction of absorbed light (the yield) reemitted as fluorescence are sensitive indicators of the photosynthetic processes occurring in the leaf. When a leaf, algae, or a solution of chlorophyll is illuminated with light filtered to remove the wave band where fluorescence occurs, the fluorescence appears as a deep red glow (just at the limit of human vision). This kind of filtering has been a staple of laboratory photosynthesis research for decades. It is relatively easy to measure chlorophyll fluorescence yield in the laboratory; however, it has been difficult to apply this technology to the canopy level. This obstacle occurs because leaves in nature are illuminated with full-spectrum sunlight, which overpowers the dim light from fluorescence, making it difficult to observe.



Fig. 2. This prototype remote sensing instrument for chlorophyll fluorescence operates at distances of up to 50 meters from the target leaf or canopy. The insert at lower left shows a target leaf being illuminated by the laser. The equipment attached to the leaf permits simultaneous measurements of photosynthesis and fluorescence for calibration. (Image courtesy Barry Osmond.)

Joe, along with Paul Falkowski (Rutgers University), Zbigniew Kolber and Dennis Klimov (Monterey Bay Research Institute), Uwe Rascher (Research Center Jülich, Institute of the Phytosphere, Germany), and Barry Osmond (former director of the Biosphere 2 Laboratory) are testing a prototype remote sensing instrument (Fig. 2) that uses a laser to create repeated pulses of fluorescence, which can be quantified as the time-varying component of the total light, even when fluorescence is a tiny fraction of the magnitude of sunlight. This instrument can be mounted on a tower or a helicopter for canopy-scale measurements. The basic principle of the instrument builds on a long history of Carnegie research. Olle Björkman (formerly a faculty member with Plant Biology, now retired) and former fellow Barbara Demmig began a line of studies in the 1980s that solidified the foundation for using fluorescence to quantify photosynthesis. Later contributions from Olle, Joe, Plant Biology faculty member Arthur Grossman, and former fellows Engelbert Wiess and Kris Niyogi extended the link between fluorescence and photosynthesis to the molecular scale.

The development of new remote sensing techniques was also a major theme in Greg's lab, where there are far-flung projects on quantifying forest disturbance and the chemical composition of forest canopies. It is relatively straightforward to estimate large-scale deforestation from satellite data, but it is difficult to even detect selective logging, the removal of scattered trees on a one-by-one basis. Yet, selective logging has important impacts on many of the world's forested ecosystems. Wrapping up five years of field-based studies, Greg's lab developed techniques to detect both the extent of selective logging in the Amazon and its impacts on the structure of the forest (Fig. 3). Along with senior technician David Knapp, Greg brought these techniques to "industrial scale" in the Carnegie Landsat Analysis System, or CLAS. CLAS provides automated detection of deforestation, selective logging, and many other types of forest disturbance using standard satellite technologies. The group is now using CLAS to map more than 20 million square kilometers of forest.

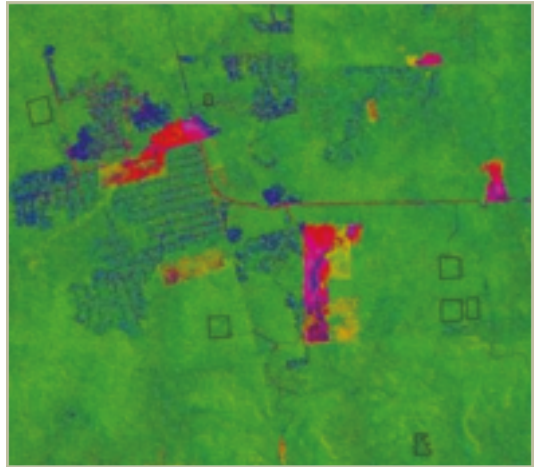


Fig. 3. This satellite imagery is interpreted to show undisturbed forest (green), deforestation (red), and selective logging (blue) in the Brazilian Amazon. The algorithm used for selective harvesting quantifies the area affected. (Image courtesy Kathy Heidebrecht.)

Another area where remote sensing techniques have been developed in Greg's lab is canopy chemistry and species identification. Until recently, remote sensing of vegetation meant primarily sensing greenness, based on a simple index, or disturbed areas, based on shape. Greenness and the shapes of disturbed areas reveal important features of an ecosystem, but the picture they provide is far from comprehensive. In particular, subtle but important changes in element cycling are often reflected in changes in the chemical composition of leaves. Responses to these changes, or to changes in climate, often involve changes in the relative abundance of the plant species that form the forest. Invasions by non-native species, which have reached crisis proportions in many of the world's ecosystems, are notoriously difficult to detect using remote sensing.

A large-scale (3-acre) water-diversion experiment in the Amazon provided Greg and Dan Nepstad (Woods Hole Research Center) an opportunity to explore techniques for quantifying the changes in the rain forest canopy in response to artificially imposed drought. Using a new generation of hyperspectral imager, with data at many wave-

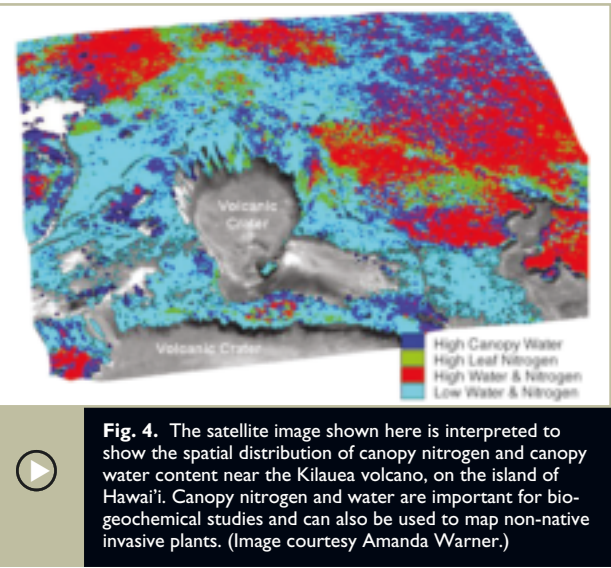


Fig. 4. The satellite image shown here is interpreted to show the spatial distribution of canopy nitrogen and canopy water content near the Kilauea volcano, on the island of Hawai'i. Canopy nitrogen and water are important for biogeochemical studies and can also be used to map non-native invasive plants. (Image courtesy Amanda Warner.)

lengths, they were able to quantify changes in the water and nitrogen content of the plant canopy. In Hawai'i, Greg and Peter Vitousek (Stanford) validated this approach by comparing remote sensing measures of canopy water and nitrogen content against direct, field-level measurements at many sites (Fig. 4). The result not only confirmed the generality of the technique, it also demonstrated that the signatures for canopy water and nitrogen can be used on Hawai'i to map the abundance and distribution of two important non-native, invasive species. Using a different approach to map invasives, Greg used satellite data from Tahiti to develop a signature for *Miconia calvescens*, a destructive invasive plant on both Tahiti and Hawai'i. The signature from Tahiti revealed previously known and unknown infestations on Hawai'i, motivating a broader application of this technology.

A final example of remote sensing technique development comes from my lab, where we are using spectral reflectance to quantify impacts of global changes (Fig. 5). My colleague Nona Chiariello (Stanford) and I are testing approaches for quantifying the sometimes subtle changes in canopy structure and chemical composition that result from warming, elevated atmospheric carbon dioxide, and a range of other treatments designed to

simulate climate conditions expected in 2100. The methods we are developing will be compatible with future deployment on satellites or aircraft. At the same time, the spectral reflectance is providing a powerful, nondestructive method for following effects of the treatments, especially changes in plant species composition and in the timing of features such as flowering and senescence.

Several of the efforts in the department focus on quantifying aspects of the carbon cycle, a critical lever in climate change. Increased carbon storage by land and ocean ecosystems, through increased photosynthesis or expansion of forests could, to some extent, decrease the urgency of decreasing emissions of greenhouse gases from human activities. On the other hand, decreased rates of carbon storage or releases from increased wildfire or other mechanisms could amplify the need for reducing human-induced greenhouse gas emissions.

In Greg's lab, one major theme of carbon research involved studies on how cattle ranching, climate change, and fire management are changing grassland and woodland ecosystems in the American Southwest. Working in southern Arizona, Greg, Stanford graduate student Winston Wheeler, programmer Bob Haxo, and others are using a combination of field, remote sensing, and modeling

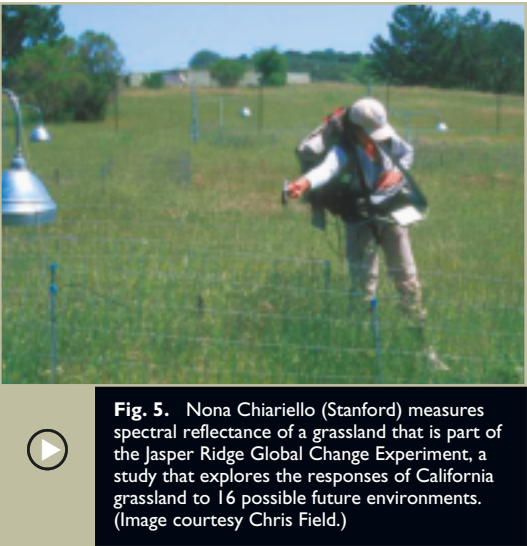


Fig. 5. Nona Chiariello (Stanford) measures spectral reflectance of a grassland that is part of the Jasper Ridge Global Change Experiment, a study that explores the responses of California grassland to 16 possible future environments. (Image courtesy Chris Field.)



Fig. 6. The Global Ecology building, completed in March 2004, is a high-performance structure. It uses a combination of careful layout, appropriate materials, and innovative mechanical and electrical systems to achieve carbon emissions per occupant that are lower by a factor of 4 to 6 than those of other new labs in California. (Inset image courtesy Peter Aaron for ESTO; large image courtesy Wenqiang Tang.)



techniques to understand changes in the extent of and carbon storage by pinyon pine/juniper woodlands. Following in the footsteps of renowned Carnegie scientist Forrest Shreve (Department of Botanical Research 1908-1948), they are studying how climate variability affects the geographic distribution of plants and how the explosion of human activities in the Southwest may change ecosystems in the coming decades. With remote sensing data from both aircraft and satellites, Greg and colleagues developed detailed geographic analyses of ecosystem condition in and around five U.S. national parks.

The department also has studies on future food security, which are closely related to the work on carbon. Stanford graduate student David Lobell, along with Greg and other collaborators, analyzed the role of climate variability and management in determining cropland yields in large parts of Mexico and the U.S. Using satellite imagery as their primary

tool, they found that agricultural yields can be predicted before harvest and that these yields are largely controlled by climate, even with improved management to increase crop growth.

Stanford graduate students Kim Nicholas Cahill, Elsa Cleland, and Claire Lunch, working with me, took a different approach to food security. Working with a large group of collaborators, we examined the sensitivity of several sectors of California agriculture to future climate change. We identified several crops as potentially sensitive to climate change in this century. The wine grape and dairy industries (two of the largest sectors of California agriculture) may be especially sensitive, and will experience greater impacts if the world's economies stick to their current dependence on fossil fuels and smaller impacts if emissions grow more slowly.

A final theme in the department over the last year was moving into our new home, which was com-



Fig. 7. Members of the Global Ecology staff are shown in 2004. First row (from left): April Villagomez, Robin Martin, Claire Lunch, Kathleen Brizgys, Yuka Otsuki-Estrada, Chris Field, and Todd Tobeck. Second row: Bob Haxo, Kim Carlson, Kathi Bump, Lisa Moore, Elsa Cleland, Mary Smith, Linda Longoria, Ismael Villa, and Angelica Vasquez. Third row: Guanghui Lin, Ulli Seibt, John Juarez, Jason Funk, David Knapp, David Lobell, Glenn Ford, Susan Finlayson, and Hugh Henry. Fourth row: Paulo Oliveira, David Kroodsmas, George Merchant, Joe Berry, Greg Asner, Eben Broadbent, Paul Sterbentz, and Lars Hedin.

pleted in March 2004 (Fig. 6). With numerous features designed to save energy and otherwise reduce its environmental impact, the building has provided many opportunities to explore practical approaches to solving some of the environmental problems we study. To the delight of the entire DGE community, we have proved that it is possible to work in a structure that is comfortable and attractive as well as energy-efficient.

Though the Department of Global Ecology is new and the group is small, we are already widely recognized as playing a leading role in the emergence

of this new field. By linking ecosystem-scale experiments, global-scale observations, and computer models, plus other kinds of synthesis, we are developing and testing novel tools to track and understand ecosystem responses to the varied conditions that we might expect in the world of the future. The world and its ecosystems are changing rapidly, in many ways. Just as a driver at night strains to see at the limit of the headlights, the changing world of tomorrow will require management at the limits of our understanding. In the Department of Global Ecology, we are proud to be improving the planet's headlights.

—Christopher Field

July 1, 2003 – June 30, 2004

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¹From August 26, 2003, to December 20, 2003

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³To December 31, 2003

⁴To October 31, 2003

⁵To July 31, 2003

⁶From October 1, 2003

⁷To August 31, 2003

⁸From September 1, 2003

⁹From April 5, 2004

¹⁰To February 1, 2004

¹¹From April 16, 2003, to July 15, 2003

¹²To December 12, 2003

¹³From January 20, 2004

¹⁴From March 16, 2004

¹⁵To February 28, 2004

¹⁶From April 16, 2003, to July 10, 2003

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THE DIRECTOR'S REPORT:

Cosmology and the Carnegie Centennial

"COLLECTIVELY, THE WORLD OF ASTRONOMY, AND MORE RECENTLY THAT OF PHYSICS, OWES AN IMMENSE DEBT TO THE CARNEGIE INSTITUTION AND ITS DISTINGUISHED ASTRONOMICAL FACULTY FOR DISCOVERING AN IMPRESSIVE FRACTION OF WHAT WE NOW TAKE FOR GRANTED ABOUT THE UNIVERSE AND ITS MAJOR CONSTITUENTS."

—Roger D. Blandford, 2004



Cosmology is one of the grandest of human endeavors—it seeks to address some of the most basic, yet awe-inspiring, questions about the origin and evolution, structure, and composition of the universe. A spectacular cosmological picture has emerged—that of a dynamic, expanding (in fact, accelerating) universe filled with objects made of shining and dark matter rushing apart at colossal speeds, the result of a titanic explosion early in its history. The known elements of matter turn out to be but a small fraction of the total matter and energy of the universe, 95% of which is dark and unseen. A continually increasing theoretical and observational foundation underlies our understanding of the universe starting from about one millionth of a second after the Big Bang to the present. New ideas about the early universe, not yet tested experimentally, are challenging standard views on the nature of space and time, matter and energy.

The history of cosmology is intertwined inseparably with that of the Carnegie Institution. The year 2004, when I write this essay, is a fitting occasion to review the history and status of both enterprises. One hundred years ago, processions of burros and horses hauled tools and equipment up an undeveloped and winding Mount Wilson trail. Certainly

no one could have foreseen the new vistas onto the universe this activity would reveal.

First, Some Brief History

It is George Ellery Hale and Andrew Carnegie to whom we owe the development of astronomy and cosmology in Pasadena. Hale passionately believed that progress in optical astronomy required the construction of large, reflecting telescopes (Fig. 1). In 1902, he secured funding from Carnegie for a giant, 60-inch reflector to be erected on Mount Wilson. In 1905, a 60-foot solar tower was completed, and in 1906, two years before the 60-inch had even begun its operations, Hale was already devising a means to construct a 100-inch reflector, which began operations in 1917. The trend continued. In 1926, Carnegie and Caltech signed an agreement to build a 200-inch (5-meter) telescope. And until about 1980, the two institutions ran Palomar jointly as the Hale Observatory. It is no exaggeration to say that for about two-thirds of the 20th century the telescopes and institutions connected with Mount Wilson and Mount Palomar dominated the world of astronomy.

Left: Gravitationally lensed galaxies show beautiful arc-like features, which are distant galaxies that have been distorted and in some cases magnified by the gravitational field of a massive cluster. This image was taken by Carnegie Fellow Mike Gladders at the Magellan 6.5-meter Baade telescope using the IMACS camera.

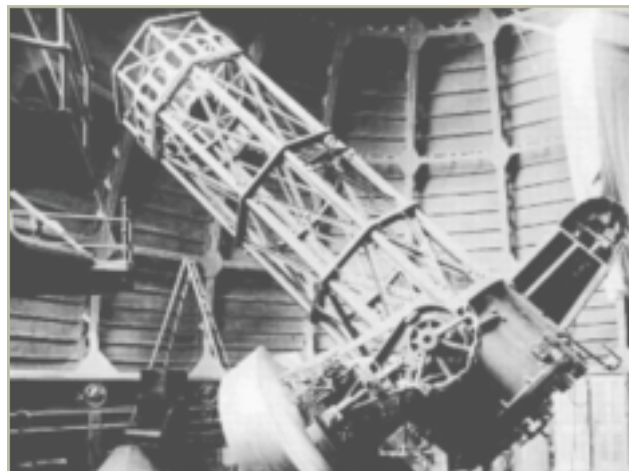


Fig. 1. George Ellery Hale is shown with the Mount Wilson 60-inch telescope, the Mount Wilson 100-inch telescope, and the

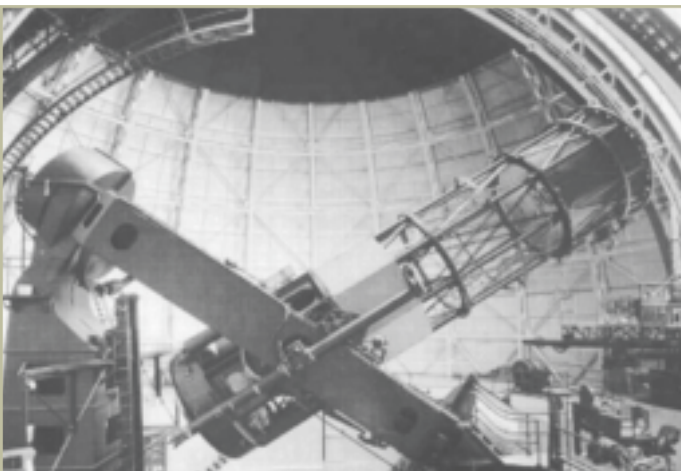
The big telescopes made possible many cosmological discoveries of the 20th century. Harlow Shapley discovered that the Sun is offset from the center of our Milky Way galaxy, toppling the almost 400-year-old Copernican model of a Sun-centered universe. Edwin Hubble discovered that our galaxy is not alone, and, spectacularly, that the more distant a galaxy is, the faster it moves away. These results ultimately led to our current picture of an expanding universe, now the backbone of modern cosmology.

Other significant discoveries included Walter Baade's concept of stellar populations, which revolutionized the study of stellar and galaxy evolution and impacted the cosmological distance scale; Allan Sandage's heroic efforts to measure the Hubble constant and the ages of globular clusters; Vera Rubin's optical rotation curves of galaxies, pivotal in establishing the presence and significance of dark matter in the universe; Sandage, Leonard Searle, and collaborators' pioneering work on the formation of the Milky Way; Steve Shectman, Alan Dressler, and their colleagues' mapping of distant galaxies, and the discovery of giant voids and immense structures in the distribution of galaxies—the cosmic web.

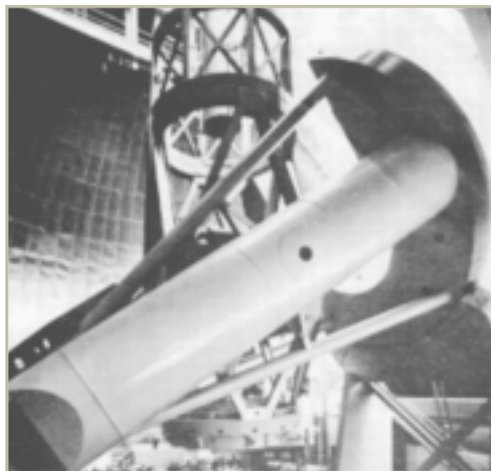
The 6.5-meter twin Magellan telescopes (Baade and Clay) are another fitting tribute to the Carnegie centennial. Astronomers at Carnegie and our partner institutions (Harvard, MIT, the University of Arizona, and the University of Michigan) are pursuing an exciting range of questions about black holes, the history of the universe, and planets around other suns, to name only a few. And as I described in my director's essay last year, ambitious new plans are now under way for the construction of the 24.5-meter Giant Magellan Telescope (GMT). As I write these words, an agreement has just been signed by Carnegie and the University of Arizona for the construction of the first of eight mirrors to be cast, and the University of Texas at Austin and Texas A&M University have joined the project. This century is beginning with as much excitement as did the previous one.

A Snapshot of Cosmology Today

A novel aspect of today's cosmology is an increasingly precise set of cosmological measurements. Both the quantity and the quality of cosmological data have advanced to the point where essentially all of the parameters are supported by an interlocking set of independent measurements. Still, there are a number of challenges. Let me describe the evidence for our current picture of the universe.



Palomar 200-inch telescope.



Hot Big Bang Cosmology

By 1915, Albert Einstein (Fig. 2) had formulated his theory of general relativity, a mathematical description of the nature of gravity. Einstein recognized that a motionless universe would be unable to remain at rest for very long—that is, it would tend to either contract from its own gravity or perhaps expand if perturbed. General relativity thus provided a physical framework for understanding the unexpected motions of galaxies observed by Hubble 14 years later. The subsequent discovery of the cosmic microwave background radiation in 1965 supported this theory and led to our current picture of an expanding hot Big Bang universe. However, Einstein missed the opportunity to predict the expansion, and introduced a new term into his equations (the cosmological constant), literally forcing the universe to be stationary. Curiously, this term, which he abandoned after Hubble's discovery, has resurfaced out of necessity with the recent discovery of dark energy.

The hot Big Bang model provides the overall mathematical and physical framework for understanding the evolution of the universe. There are four major pieces of observational support for the basic Big Bang picture: the expansion of the universe; the large-scale homogeneity and isotropy of galaxies and large-scale structure; the remnant 3-degree Kelvin cosmic microwave background radi-

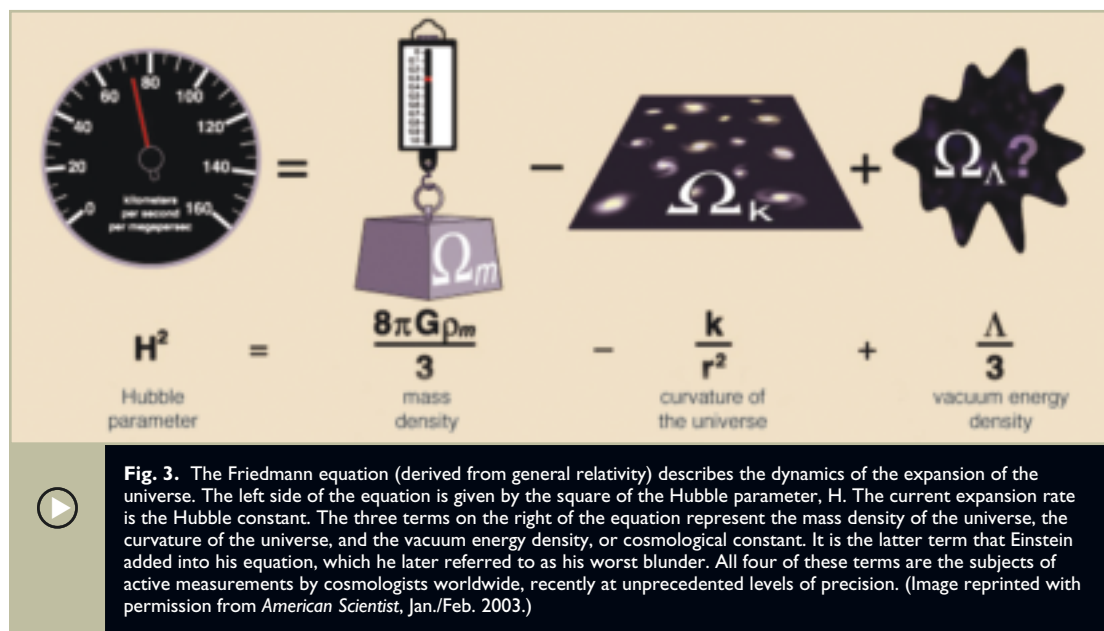
ation; and the relative abundances of the light elements (i.e., hydrogen, helium, deuterium).

The Expansion of the Universe. Hubble's discovery of the simple correlation between galaxy distance and recession velocity led to the challenge of estab-



Fig. 2. Albert Einstein is shown here in 1931 with astronomers at the Hale Library of the Observatories' offices on Santa Barbara Street. Einstein came to visit Pasadena after learning of Hubble's discovery of the expansion of the universe. The portrait of George Ellery Hale, seen in the picture, still hangs in the same place in the library today. From left to right are Milton Humason, Edwin Hubble, Charles St. John, Albert Michelson, Albert Einstein, William Campbell, and Walter Adams.





lishing accurate distances over cosmologically large scales and obtaining an accurate value for the expansion rate (the Hubble constant) (Fig. 3). One of the main reasons for proposing and building the Hubble Space Telescope was to increase the precision in these measurements, and the expansion rate was designated one of three “Key Projects.” This Key Project involved an international group of 30 astronomers, including Carnegie’s Barry Madore, Dan Kelson, and myself as one of three principal investigators. In 2001, our team published a value of 72 kilometers/second/megaparsec, with an uncertainty of 10%. This result was confirmed in 2003 by an independent group working with the Wilkinson Microwave Anisotropy Probe (WMAP), measuring fluctuations in the cosmic microwave background temperature. This group obtained a Hubble constant of 71. These results also overlap, to within measurement uncertainties, with those of Allan Sandage and collaborators.

Large-Scale Homogeneity and Isotropy. As we know from studying the distribution of galaxies and clusters on the sky, the universe is actually neither homogeneous nor isotropic on all scales. There is a rich structure to the distribution of matter in the

universe. This structure is visible in two dimensions if one simply plots the positions of galaxies projected on the sky. However, measuring the actual three-dimensional distribution of this structure requires the measurement of the distances to galaxies by measuring velocities and then applying Hubble’s relation between velocity and distance—the Hubble law. These measurements have advanced considerably with the development of new spectrographs; for example, Steve Sheckman’s fiber spectrograph for the du Pont telescope, which provided the means to measure about one hundred galaxy redshifts at once; and Alan Dressler’s Magellan IMACS spectrograph. These observations have revealed galaxy clusters and superclusters, and large voids, walls, and filaments, some of them extending over 300 million light-years. Over larger volumes, however, the distribution of galaxies approaches homogeneity.

The Cosmic Microwave Background. In the first 400,000 years after the Big Bang, the temperature was high enough to keep all of the matter in the universe ionized, preventing electrons from combining with protons to form atoms. During this time, photons continually scattered off the free

electrons. As the universe expanded and cooled, electrons began to combine with protons into atoms. Thereafter, photons could directly journey through the universe without being continually scattered and deflected. The radiation that last scattered the electrons has now cooled to a temperature of 2.725 ± 0.002 K, and has been redshifted by the expansion so that it is now detected at microwave wavelengths. The serendipitous 1965 discovery of this cosmic microwave background radiation by Arno Penzias and Robert Wilson provides one of the strongest pieces of evidence in support of a hot Big Bang. This radiation has the characteristic spectrum predicted by Big Bang theory and is very isotropic, exhibiting a very high degree of uniformity across the sky, also as predicted.

Temperature Differences in the Cosmic Microwave Background Radiation. One of the striking aspects characterizing the cosmic microwave background radiation is its uniformity: to a few thousandths of a percent(!), its temperature is virtually the same everywhere in the sky. But in 1992, the Cosmic Background Explorer (COBE) satellite detected tiny residual fluctuations in the temperature. Since then, many additional experiments have confirmed the COBE result, including those conducted by the WMAP satellite in 2003, which measured temperature fluctuations over the whole sky to a resolution of 10-50 times greater than COBE could.

The temperature fluctuations in the cosmic microwave background contain vast information on the physical state of the early universe. Associated with these fluctuations are fluctuations in the density of matter in the early universe. High-density regions grow larger with time because of the attraction of gravity. However, the outward pressure from photons, acting counter to the force of gravity, sets up oscillations whose frequency spectrum can be predicted. The precise nature of the oscillations depends upon almost all cosmological parameters: the expansion rate of the universe, the spatial curvature of the universe, the densities of ordinary and dark matter, and the amount of dark energy.

Measurements of the temperature fluctuations in the cosmic background radiation yield a value of

the ordinary matter (or baryon) density that is in excellent agreement with, and independent of, other measurements. In addition, combined with measurements of the large-scale structure of the universe, the WMAP results yield a Hubble constant of 71 kilometers per second per megaparsec as discussed above, and a universe with the present mass-energy fraction of one-third matter and two-thirds dark energy, in excellent agreement with other measurements. The results are also consistent with a universe of flat spatial geometry, adding further confidence to the overall current standard cosmological model.

The Abundance of the Light Elements. One of the major successes of the Big Bang theory is the agreement between observations of the present light-element abundances and the predictions of the abundances of elements formed in the Big Bang. Hydrogen, helium, and lithium were processed about three minutes after the Big Bang, but elements heavier than lithium were formed later in the central furnaces of stars. The visible matter in the universe is observed to be composed mainly of hydrogen (about 75%), helium (about 25%), and only trace amounts of deuterium, lithium, and all of the other elements in the periodic table up through carbon, oxygen, and iron (those ingredients vital to our existence on Earth). The exact abundances of the elements produced just after the Big Bang can be calculated very precisely, and the predicted abundances for these different light elements agree extremely well with the observed abundances, a powerful test of Big Bang cosmology.

Dark Matter

The first hints of dark matter emerged over 70 years ago with the work of Caltech's Fritz Zwicky. However, it was decades before sufficient independent evidence led to a solid consensus on its existence. Instrumental in this effort was the work of Carnegie's Vera Rubin and her research on the orbits of stars in the outer parts of spiral galaxies. Collaborating with Kent Ford, Rubin showed that the velocities of stars in the outer parts of galaxies were faster than expected, assuming that the masses of galaxies could be gauged from the luminous matter. That is, the stars were moving too

fast and could not remain bound to the galaxies by gravity unless the galaxy masses were higher; that is, unless there was some unseen mass in the galaxies—dark matter.

Today we infer that, remarkably, only 5% of the overall mass-energy density of the universe can be accounted for by ordinary matter. However, only about one-fifth of this matter is observed in luminous form. Over the past decade, extensive searches for the additional 4% of unseen ordinary material (baryons) have been carried out. It appears that most of this additional mass is warm gas associated with groups of galaxies, whereas the remainder is located within galaxies, composed of both stars and cold gas.

While 4% of the overall density may be in dark baryons, other evidence overwhelmingly points to the existence of additional, nonbaryonic, dark matter, comprising about 25% of the overall total (mass plus energy) density. The evidence for nonbaryonic dark matter has mounted with several independent and increasingly higher precision measurements.

In addition to Rubin's and others' rotation curves, measurements of the velocities of individual stars within galaxies, small satellite galaxies in the outer halos of the Milky Way, and galaxies within clusters all point to significant amounts of unseen matter. Again, without this dark matter, these stars and satellites would escape from the galaxies or clusters in which they reside. Another way to infer

the existence of dark matter is from observations of distant galaxies located behind massive clusters of galaxies. Einstein's theory of general relativity predicts that matter will curve space. Massive clusters of galaxies can therefore act as giant magnifying and distorting lenses, where the images of background galaxies can be drawn out into arc-like features, with their brightnesses amplified (frontispiece). In addition, temperature measurements of the X-ray gas (the most abundant component of ordinary matter within clusters) yield yet another estimate of the dark matter mass in clusters. There are numerous other types of measurements, but all the results have converged to the common conclusion that most of the matter in the universe is dark, and that there is about five times more dark than luminous matter.

What is the dark matter? To date, this remains an unsolved problem and a very active area of research. The current favored hypothesis from particle physics is that it is comprised of some new, undetected type of particle that survived the early universe. There are many direct ongoing searches for the dark matter particles themselves, and it is hoped that they will eventually be discovered either in laboratories or by producing the dark matter particles in large accelerators. Such experiments are now under way worldwide.

Dark Energy

A decade ago, most astronomers and physicists expected that if they could make measurements of the more distant universe they would be able to observe the expansion velocity of the universe

Fig. 4. Images of five nearby spiral galaxies, in which supernovae have recently been discovered as part of the Carnegie Supernova Project (CSP), were obtained at the 40-inch Swope telescope at Las Campanas and are shown here courtesy of CSP postdoctoral fellow Gaston Folatelli. The goal of the CSP is to observe supernovae at a range of distances over a range of colors to characterize the nature of the mysterious dark energy component of the universe.



slowing down over time. Just as the velocity of an object hurled upward on the Earth is slowed by the force of gravity, it was reasoned that matter in the universe would slow its expansion. It was therefore a surprise that when measurements of distant supernovae became feasible, they failed to reveal a deceleration in the expansion. Just the opposite effect was uncovered.

Supernovae, the result of thermonuclear explosions of stars, are so bright that they can briefly rival the luminosities of the galaxies in which they reside, and therefore can be observed to great distances (Fig. 4). Sensitive, wide-area electronic detectors such as charge-coupled devices (CCDs) have opened up the possibility of searches for large samples of faint and distant supernovae. Observations by two independent groups in the late 1990s found that supernovae at high redshifts are fainter in comparison with those nearby than would be expected if the expansion of the universe were slowing over time. It is of course possible that astrophysical effects of a noncosmological nature could make supernovae at higher redshifts *appear* fainter than those observed locally. For example, differing amounts or types of dust could make the distant supernovae appear to be fainter. Different chemical compositions, changes in supernovae over time, and other effects could also plausibly cause differences in their intrinsic luminosities. However, many groups have searched for these potential systematic effects, but have been unable to find any evidence for them. Moreover, recent observations by the WMAP satellite, based on entirely indepen-

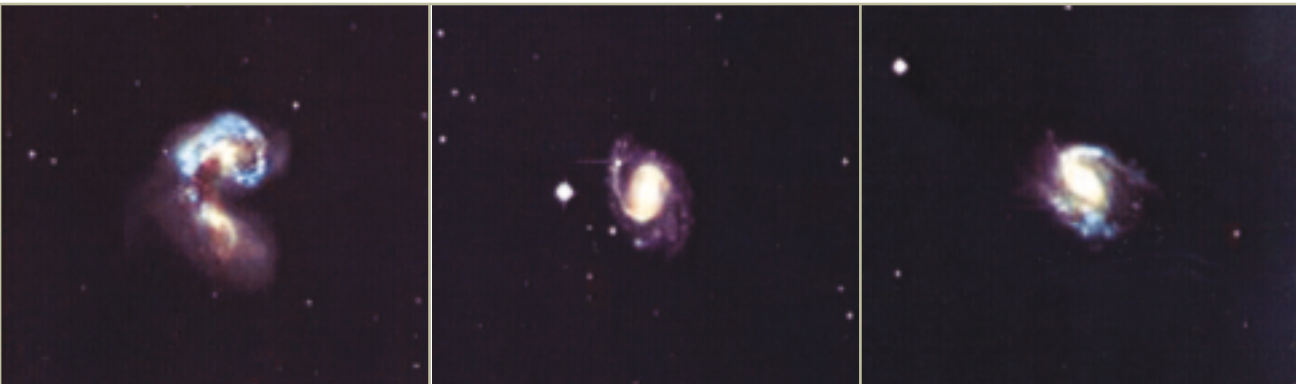
dent physics, yield results entirely consistent with the supernova data.

These observational results argue for a universe in which one-third of the overall density is in the form of matter (ordinary plus dark) and two-thirds is in some different form, perhaps dark energy. The observations suggest that dark energy has a large, negative pressure (and so acts counter to gravity) and does not cluster gravitationally with matter but fills all of space. Dark energy currently has no explanation. It has been characterized by many leading physicists as the most important issue facing all of particle physics and cosmology.

Inflation

The standard hot Big Bang cosmology assumes that the universe is homogeneous and isotropic, without providing any explanation why this should be so. Yet the microwave background radiation is indeed observed to be remarkably smooth. Why should the temperature, density, and properties of completely disconnected regions all across the sky be so remarkably similar? According to the Big Bang model, the foundation of which is general relativity, the geometry of the universe can have a positive, negative, or zero curvature (a flat universe). Observations are consistent with a universe remarkably close to flat, but the standard Big Bang cosmology again provides no explanation for this. Homogeneity, isotropy, and flatness all find a simple explanation in a theory called inflation.

The theory of inflation, based on elementary-parti-



cle physics, predicts that early in the universe, the energy associated with the vacuum of space caused a very rapid expansion and increase in size. Small, smooth regions were expanded exponentially by this inflation to sizes that are larger than our currently observable universe. It is as a result of this rapid expansion that the universe's spatial geometry was stretched out and became flat. And small density inhomogeneities became the seeds that have grown into the galaxies and clusters of galaxies that we see today. Thus, inflation naturally provides a way to explain both the smoothness observed in the microwave background radiation on large scales, as well as the detailed distribution of galaxies on smaller scales. Remarkably, the spectrum of oscillations observed in the microwave background fluctuations agree to very high precision with the predictions of inflation. Further (and more stringent) tests of inflation will come with future measurements of gravitational waves, an additional prediction of inflation.

Later Evolution of the Universe

As we have seen, our first glimpse of the universe occurs about 400,000 years after the Big Bang, when radiation was last scattered. Thereafter, as the universe expanded and cooled, the conditions became propitious for the formation of stars, galaxies, black holes, and other objects seen today. In recent years, a new window on the early universe has opened as telescopes have become more powerful. These deeper images of the sky have revealed the presence of galaxies in the distant universe; we are seeing them as they were at an earlier time, when they were younger. By measuring objects at differing distances, we witness the evolution of the universe.

Carnegie astronomers continue to play a pivotal role in studying and understanding the early universe. Pat McCarthy, Eric Persson, Alan Dressler, Dan Kelson, Gus Oemler, John Mulchaey, and Carnegie Fellow Mike Gladders have been using the telescopes at Las Campanas, the Hubble Space Telescope, and the Chandra X-ray telescope to study distant galaxies, groups of galaxies, and clusters of galaxies. These and other studies have shown that galaxies appear to have started to form very early, with galaxy clusters and groups assem-

bling more slowly over time. This picture is broadly consistent with theoretical models for the assembly of galaxies and structure in the universe, models that incorporate the early initial conditions from inflation and include dark matter. The process of forming galaxies is very dynamic—galaxies merge and collide (as Carnegie's François Schweizer has studied for many years), transform in appearance, have episodic bursts of star formation, and emit copious amounts of radiation spanning the X-ray, ultraviolet, through the optical, infrared, and radio parts of the spectrum. However, to observe directly the first light in the universe, the formation of the first stars, and first galaxies we must await higher resolution and sensitivity, one of the goals of the Giant Magellan Telescope. We know almost nothing of this epoch; it has been dubbed the "dark ages."

Some galaxies have nuclei with luminosities that can exceed those of ordinary galaxies by factors of hundreds. Strong evidence over the past four decades suggests that the engines powering the various kinds of observed active nuclei (the most luminous of which are quasars) are black holes with masses ranging from a million to a billion times the mass of our Sun. Most likely these black holes grew by mergers and the accretion of gas onto high-density regions of matter. Work by Carnegie staff members Luis Ho and Alan Dressler and their collaborators has shown that these supermassive black holes are found in the nuclei of all galaxies so far studied. Unrecognized until recently, it appears that somehow the black hole knows about the galaxy environment in which it is situated—the mass of the black hole is closely related to the properties of its host galaxy. These observations have important implications for understanding how galaxies assemble and how this process is related to black hole formation. The details of the formation of such supermassive objects at high redshift remain to be understood and must again await future telescopes.

Two other interesting probes of the chemical and dynamical evolution of the universe come from studies of distant quasars, as well as detailed studies of our own Milky Way galaxy. Quasars can be used as bright-light sources against which to study the

distribution and chemical composition of matter throughout the universe—the research of staff member Michael Rauch and staff member emeritus Ray Weymann. These and other studies have helped to reveal both the vast cosmic web of galaxies, which has evolved into our present-day universe, and the detailed compositions and physical conditions of the gas in the early universe. The study of distant galaxies and quasars is one way to probe the evolution of the universe. The inverse and complementary approach is to study the chemical and dynamical history of the Milky Way by observing nearby stars of differing chemistries and ages. George Preston, Steve Shectman, Andy McWilliam, and Ian Thompson have an ambitious program at Las Campanas surveying for and discovering stars of very low chemical abundances, which are among the earliest-formed objects in the Galaxy.

A new class of extragalactic objects—gamma-ray bursts (GRBs)—has emerged, with the exciting recent discovery that many of these objects lie at cosmological distances. These extremely luminous objects emit most of their extraordinary energy at gamma-ray frequencies, and do so in the space of only a few seconds. Because they are so bright, they provide a new beacon for probing the earliest epochs of star formation. The study of these objects is being conducted at Carnegie by Edo Berger, our first Carnegie-Princeton Fellow. The field has advanced rapidly with the capability of satellites to measure the positions of these sources accurately and rapidly, allowing follow-up with ground-based telescopes. In a very recent advance, optical spectra of some objects have shown a connection between GRBs and supernovae. In October 2004, NASA launched a new gamma-ray mission called Swift. Swift is now providing very accurate locations of the targets so that they can immediately be observed from the ground. Edo Berger, in collaboration with a number of Carnegie and Caltech astronomers, is using the unique rapid instrument-changing capability of Magellan to

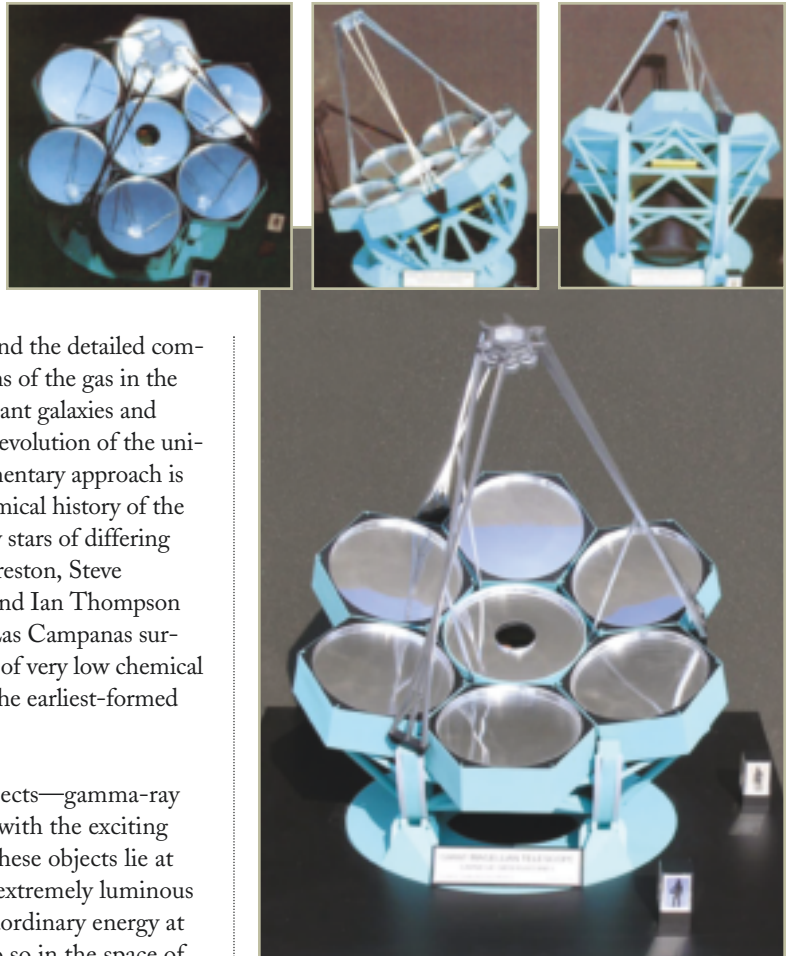


Fig. 5. This is a model of the Giant Magellan Telescope, which is made of seven 8.4-meter mirrors, six of them around the seventh. The model is shown from four different perspectives. The technology for this telescope is being built on the heritage of the Magellan telescopes.



interrupt the observing on nights when new GRBs are detected by Swift and immediately take data before the bursts fade. His goal is to study the star-formation history early in the universe and use the bright GRBs as backlights to illuminate the distribution of objects and measure their chemical composition in the early universe, similarly to quasar studies. A whole new window is opening with this burgeoning field. In fact, the 40-inch Swope telescope provided immediate follow-up observations of the first gamma-ray burst detected by Swift.



Fig. 6. The research staff members of the Carnegie Observatories pose in the Hale Library in October 2004. Standing from left: Michael Rauch, Barry Madore, Stephen Shectman, Patrick McCarthy, Dan Kelson, Andrew McWilliam, and Alan Dressler. Seated from left: Ian Thompson, Luis Ho, Eric Persson, Wendy Freedman, George Preston, François Schweizer, and John Mulchaey. Missing are Augustus Oemler, Jr., and Allan Sandage.

New Observational Tools

In the upcoming decade, a new array of initiatives in space and on Earth are planned to address many of the current cosmological questions. The James Webb Space Telescope (JWST), a NASA 6-meter telescope optimized to detect infrared wavelengths, is scheduled for launch in 2011. Its primary goal will be to detect light from the first stars in the universe, to illuminate the “dark ages,” and to observe directly the time when the universe became reionized. A strong motivation for the Giant Magellan Telescope project (Fig.5) is to be operational during the Webb era to provide spectra (and detailed physical information) for many of the objects discovered by the Webb.

On the ground, an 8.4-meter survey telescope is planned for very rapid sky coverage over a very wide field on the sky. The Large Synoptic Survey Telescope (LSST) will survey the northern sky in four colors, once every three nights. One of its primary goals will be to study dark matter through weak gravitational lensing and produce many type Ia supernova candidates useful for studying dark energy. These objects can be followed spectroscopically by other ground-based telescopes, such as Magellan and the GMT.

In addition to these planned optical/infrared telescopes, the Atacama Large Millimeter Array (ALMA) is now under construction at high altitude (5,000 meters) in northern Chile. Targets studied

with this telescope will be very well suited for observations from Las Campanas. Consisting of a collection of 64, 12-meter antennas, ALMA is a collaboration involving Europe, the U.S., and possibly Japan. Long-wavelength radiation is insensitive to obscuration by dust, and so ALMA will be capable of detecting and studying the earliest galaxies in the universe, especially those that may be enshrouded in dust and therefore inaccessible to optical telescopes. ALMA will also probe deep into the dust-obscured cocoons where new stars and planets are forming and will thus be an important complement to the GMT and the Webb.

The Webb, ALMA, and LSST will be capable of finding tremendous numbers of distant objects in the universe, but a much larger telescope is needed to collect sufficient light for the necessary spectroscopic data required to characterize and understand these objects. This is the province of the Giant Magellan Telescope. The GMT is being optimized for optical and near-infrared wavelengths designed for faint-object spectroscopy using adaptive optics to correct for the turbulence in the Earth's atmosphere. The potential of the GMT for addressing many of the outstanding questions in cosmology, as well as for searching for extrasolar planets, another exploding field, is extraordinarily exciting.

Summary

This century has witnessed a complete overhaul of our conceptions about the universe—its scale, its history, its composition, and its future. A physical model relates the earliest moments of the universe to the observed universe today and not only qualitatively describes the overall structure and evolution, but quantitatively makes predictions, which are being tested and are passing such tests at ever greater precision. Interestingly, astronomy has led the way in the revolutionary discoveries of dark matter and dark energy, which have far-reaching implications for understanding fundamental physics and the nature of particles and forces in the universe.

There are still fundamental pieces missing from this emerging new cosmological framework. I find it hard to imagine, with 95% of the universe in unfamiliar forms of dark matter and dark energy, that there are not some surprises yet to be revealed. Hence, the discovery potential for cosmology remains bright. Plans for the next generation of telescopes hold the promise of addressing some of the most fundamental questions in cosmology, indeed some of deepest questions that humanity has posed. We look forward to the next century of cosmological discoveries, and of the Carnegie Observatories!

—Wendy L. Freedman
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CAPITAL SCIENCE LECTURES AND OTHER EVENTS—FOURTEENTH SEASON 2003-2004

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Stanford University School of Medicine and Director,
Institute for Cancer/Stem Cell Biology and Medicine,
Stanford University Medical Center)
November 20, 2003

Exploring the Universe in the New Millennium, Wendy Freedman
(Crawford H. Greenewalt Director, Carnegie Observatories)
February 5, 2004

Meeting the Energy-Climate Challenge, John Holdren
(John F. Kennedy School of Government, Harvard University)
March 11, 2004

The Long and Short of Long-term Memory, Eric Kandel
(Center for Neurobiology and Behavior, Columbia University,
and Howard Hughes Medical Institute)
April 1, 2004

Galileo's Life and Times, Dava Sobel
(Former *New York Times* science writer)
April 29, 2004

The First Stars and Galaxies in the Universe, Alan Dressler
As part of the Smithsonian Resident Associate Program
(Staff astronomer, Carnegie Observatories)
June 7, 2004

Reader's Note

In this section, any discussion of spending levels or endowment amounts are on a cash or cash-equivalent basis. Therefore, the funding amounts presented do not reflect the impact of capitalization, depreciation, or other non-cash items.

The primary source of support for Carnegie Institution of Washington's activities continues to be its endowment. This reliance has led to an important degree of independence in the research program of the institution. This independence is anticipated to continue as a mainstay of Carnegie's approach to science in the future.

At June 30, 2004, the endowment was valued at approximately \$580.6 million and had a total return (net of management fees) of 16.0%. The annualized five-year return for the endowment was 9.4%.

For a number of years, Carnegie's endowment has been allocated among a broad spectrum of asset classes including fixed-income instruments (bonds), equities (stocks), absolute return investments, real estate partnerships, private equity, and natural resources partnerships. The goal of diversifying the endowment into alternative assets is to reduce the volatility inherent in an undiversified portfolio while generating attractive overall performance.

In its private equity allocation, the institution accepts a higher level of risk in exchange for a higher expected return. By entering into real estate partnerships, the institution in effect, holds part of its endowment in high-quality commercial real estate, deriving both the possibility of capital appreciation and income in the form of rent from tenants. Along with the oil and gas partnership, this asset class provides an effective hedge against inflation. Finally, through its investments in absolute return partnerships and hedge funds, the institution seeks to achieve long-term returns similar to those of traditional U.S. equities with reduced volatility and risk.

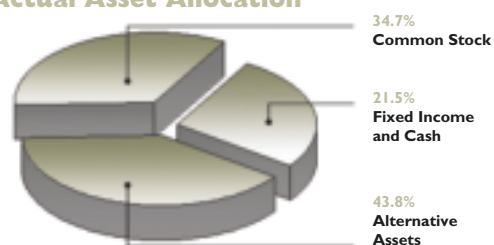
The finance committee of the board regularly examines the asset allocation of the endowment and readjusts the allocation, as appropriate. The institution relies upon external managers and part-

nerships to conduct the investment activities, and it employs a commercial bank to maintain custody.

The following chart shows the allocation of the institution's endowment among the asset classes it uses as of June 30, 2004:

	Target Allocation	Actual Allocation
Common Stock	35.0%	34.7%
Alternative Assets	50.0%	43.8%
Fixed Income and Cash	15.0%	21.5%

Actual Asset Allocation



Carnegie's investment goals are to provide high levels of current support to the institution and to maintain the long-term spending power of its endowment. To achieve this objective, it employs a budgeting methodology that provides for:

- averaging the total market value of the endowment for the three most recent fiscal years, and
- developing a budget that spends at a set percentage (spending rate) of this three-year market average.

Since the early 1990s, this budgeted spending rate has been declining in a phased reduction, moving towards an informal goal of a spending rate of 4.5%. For the 2003-2004 fiscal year, the rate was budgeted at 5.15%. While Carnegie has been reducing this budgeted rate by between 5 and 10 basis points a year, there has also been continuing, significant growth in the size of the endowment. The result has been that, for the 2003-2004 fiscal year, the actual spending rate (the ratio of annual spending from the endowment to actual endowment value at the conclusion of the fiscal year in which the spending took place) was 4.84%.

Financial Profile (unaudited) For the year ending June 30, 2004

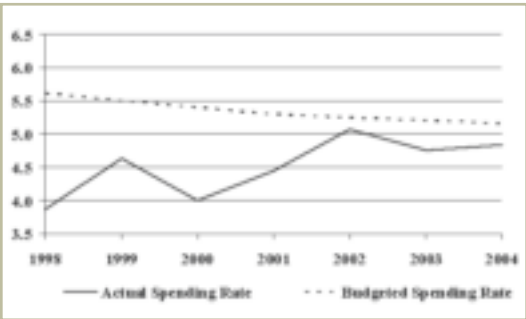
Carnegie Funds Spending Over Seven Years (Dollars in Millions)

FY	97-98	98-99	99-00	00-01	01-02	02-03	03-04
Carnegie Funds Spending	\$ 16.4	\$ 20.9	\$ 20.0	\$ 22.8	\$ 25.5	\$ 25.0	\$ 28.1 *
Actual Market Value at June 30	\$423.3	\$451.6	\$477.9	\$512.0	\$501.8	\$525.7	\$580.6
Actual Spending as % of Market Value	3.87%	4.63%	4.18%	4.45%	5.07%	4.76%	4.84% *
Planned Spending Rate in Budget	5.61%	5.50%	5.40%	5.30%	5.25%	5.20%	5.15%

* Includes \$2.1 million of expenditures that were reimbursed to the endowment in early fiscal 04-05. The sources of funds were Carnegie revenues not included in the endowment budget process. If these \$2.1 million are deducted from endowment spending, the actual spending rate is 4.48%.

The table above compares the planned versus the actual spending rates, as well as the market value of the endowment from 1997-1998 with the most recently concluded fiscal year, 2003-2004:

Budget and Actual Spending Rates



Within Carnegie’s endowment, there are a number of “Funds” that provide support either in a general way or in a targeted way, with a specific, defined purpose. The largest of these is the Andrew Carnegie Fund, begun with the original gift of \$10 million. Mr. Carnegie later made additional gifts totaling another \$12 million during his lifetime. Together these gifts are now valued at over \$519 million.

Unaudited

The following table shows the amount in the principal funds within the institution’s endowment as of June, 2004.

Principal Funds Within Carnegie’s Endowment

Andrew Carnegie	\$519,755,512
Mellon Matching	12,352,741
Astronomy Funds	10,997,747
Anonymous	8,492,800
Anonymous Matching	8,220,673
Capital Campaign	7,746,873
Wood	6,378,038
Golden	4,622,845
Science Education Fund	2,750,806
Colburn	2,249,457
McClintock Fund	1,855,964
Bush Bequest	1,404,611
Endowed Fellowships	1,226,149
Starr Fellowship	887,990
Roberts	501,719
Lundmark	368,661
Hollaender	287,572
Forbush	162,933
Hale	133,078
Green Fellowship	130,062
Harkavy	127,449
Endowed Staff, Observatories	116,029
Total	590,769,709

*Independent Auditors' Report**The Audit Committee of the
Carnegie Institution of Washington:*

We have audited the accompanying statements of financial position of the Carnegie Institution of Washington (Carnegie) as of June 30, 2004 and 2003, and the related statements of activities and cash flows for the years then ended. These financial statements are the responsibility of Carnegie's management. Our responsibility is to express an opinion on these financial statements based on our audits.

We conducted our audits in accordance with auditing standards generally accepted in the United States of America. Those standards require that we plan and perform the audits to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audits provide a reasonable basis for our opinion.

In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of the Carnegie Institution of Washington as of June 30, 2004 and 2003, and its changes in net assets and its cash flows for the years then ended, in conformity with accounting principles generally accepted in the United States of America.

Our audits were made for the purpose of forming an opinion on the basic financial statements taken as a whole. The supplementary information included in the schedules of expenses is presented for purposes of additional analysis and is not a required part of the basic financial statements. Such information has been subjected to the auditing procedures applied in the audits of the basic financial statements and, in our opinion, is fairly presented in all material respects in relation to the basic financial statements taken as a whole.

KPMG LLP

November 5, 2004

Statements of Financial Position

June 30, 2004 and 2003

	2004	2003
Assets		
Cash and cash equivalents	\$518,726	631,216
Accrued investment income	99,044	98,668
Contributions receivable, net (note 2)	7,155,007	6,561,772
Accounts receivable and other assets	8,425,062	8,877,030
Bond proceeds held by trustee (note 6)	18,209,191	29,536,629
Investments (notes 3 and 14)	590,769,709	532,023,413
Property and equipment, net (notes 4, 5 and 6)	144,813,240	133,195,832
Total assets	\$769,989,979	710,924,560
Liabilities and Net Assets		
Liabilities:		
Accounts payable and accrued expenses	\$4,115,909	5,083,899
Deferred revenue (note 5)	34,695,018	35,523,865
Bonds payable (note 6)	64,670,359	64,715,672
Accrued postretirement benefits (note 8)	13,670,000	11,359,000
Total liabilities	117,151,286	116,682,436
Net assets (note 9):		
Unrestricted:		
Board designated:		
Invested in property and equipment, net	63,657,053	62,492,924
Designated for managed investments	518,969,269	462,571,402
Undesignated	5,051,412	6,049,088
Total unrestricted net assets	587,677,734	531,113,414
Temporarily restricted	25,910,003	24,207,950
Permanently restricted	39,250,956	38,920,760
Total net assets	652,838,693	594,242,124
Commitments and contingencies (notes 10, 11 and 12)		
Total liabilities and net assets	\$769,989,979	710,924,560

See accompanying notes to financial statements.

Statements of Activities

Years ended June 30, 2004 and 2003

2004

2003

	Unrestricted	Temporarily restricted	Permanently restricted	Total	Unrestricted	Temporarily restricted	Permanently restricted	Total
Revenues and support:								
External revenue:								
Grants and contracts	\$22,458,366	—	—	22,458,366	24,705,588	—	—	24,705,588
Contributions and gifts (note 13)	1,246,482	5,335,795	106,696	6,688,973	18,130,285	5,149,505	1,090,549	24,370,339
Net losses on disposals of property	(318,211)	—	—	(318,211)	(18,012)	—	—	(18,012)
Other income	3,968,740	—	—	3,968,740	1,683,264	—	—	1,683,264
Net external revenue	27,355,377	5,335,795	106,696	32,797,868	44,501,125	5,149,505	1,090,549	50,741,179
Investment income, net (note 3)	80,749,277	6,015,449	—	86,764,726	32,665,818	1,926,187	37,354	34,629,359
Other (note 9):								
Net assets released from restrictions	9,649,191	(9,649,191)	—	—	6,321,584	(6,321,584)	—	—
Matching of endowment	(223,500)	—	223,500	—	—	—	—	—
Total revenues and other support	117,530,345	1,702,053	330,196	119,562,594	83,488,527	754,108	1,127,903	85,370,538
Expenses:								
Program expenses:								
Terrestrial Magnetism	9,562,368	—	—	9,562,368	8,299,433	—	—	8,299,433
Observatories	12,807,318	—	—	12,807,318	9,356,520	—	—	9,356,520
Geophysical Laboratory	11,903,842	—	—	11,903,842	11,665,517	—	—	11,665,517
Embryology	6,347,077	—	—	6,347,077	6,984,748	—	—	6,984,748
Plant Biology	10,371,832	—	—	10,371,832	8,551,064	—	—	8,551,064
Global Ecology	2,336,303	—	—	2,336,303	2,516,856	—	—	2,516,856
Other programs	1,161,863	—	—	1,161,863	1,422,287	—	—	1,422,287
Total program expenses	54,490,603	—	—	54,490,603	48,796,425	—	—	48,796,425
Administrative and general expenses	6,475,422	—	—	6,475,422	5,634,657	—	—	5,634,657
Total expenses	60,966,025	—	—	60,966,025	54,431,082	—	—	54,431,082
Increase in net assets	56,564,320	1,702,053	330,196	58,596,569	29,057,445	754,108	1,127,903	30,939,456
Net assets at beginning of year	531,113,414	24,207,950	38,920,760	594,242,124	502,055,969	23,453,842	37,792,857	563,302,668
Net assets at end of year	\$587,677,734	25,910,003	39,250,956	652,838,693	531,113,414	24,207,950	38,920,760	594,242,124

See accompanying notes to financial statements.

Statements of Cash Flows

Years ended June 30, 2004 and 2003

	2004	2003
Cash flows from operating activities:		
Increase in net assets	\$58,596,569	30,939,456
Adjustments to reconcile increase in net assets to net cash provided by (used in) operating activities:		
Depreciation	7,794,105	6,009,836
Net gains on investments	(80,363,758)	(29,639,941)
Contributions of stock	(1,261,267)	(79,675)
Losses on disposals of property	318,211	18,012
Amortization of bond issuance costs and discount	46,574	57,347
Contributions and investment income restricted for long-term investment	(1,708,636)	(2,662,965)
(Increase) decrease in assets:		
Receivables	(141,267)	(2,438,973)
Accrued investment income	(376)	(21,900)
Increase (decrease) in liabilities:		
Accounts payable and accrued expenses	(967,990)	1,108,230
Deferred revenue	(828,847)	713,472
Accrued postretirement benefits	2,311,000	723,000
Net cash provided by (used in) operating activities	(16,205,682)	4,725,899
Cash flows from investing activities:		
Acquisition of property and equipment	(9,333,952)	(4,550,914)
Construction of telescope, facilities, and equipment	(10,423,095)	(7,692,135)
Proceeds from sales of property and equipment	27,323	—
Investments purchased	(260,313,717)	(241,085,299)
Proceeds from investments sold or matured	283,192,446	246,224,876
Purchases of investments by bond trustee	—	(29,536,546)
Proceeds from sales of investments by bond trustee	11,327,438	—
Net cash provided by (used in) investing activities	14,476,443	(36,640,018)
Cash flows from financing activities:		
Proceeds from bond issuance	—	30,000,000
Bond issuance costs capitalized	(91,887)	(295,594)
Proceeds from contributions and investment income restricted for:		
Investment in endowment	360,025	410,100
Investment in property and equipment	1,348,611	2,252,865
Net cash provided by financing activities	1,616,749	32,367,371
Net increase (decrease) in cash and cash equivalents	(112,490)	453,252
Cash and cash equivalents at beginning of year	631,216	177,964
Cash and cash equivalents at end of year	\$518,726	631,216
Supplementary cash flow information:		
Cash paid for interest	\$1,917,108	1,165,587
Noncash activity – contributions of stock	1,261,267	79,675

See accompanying notes to financial statements.

(I) Organization and Summary of Significant Accounting Policies

Organization

The Carnegie Institution of Washington (Carnegie) conducts advanced research and training in the sciences. It carries out its scientific work in six research centers located throughout the United States and at an observatory in Chile. The centers are the Departments of Embryology, Plant Biology, Terrestrial Magnetism, and Global Ecology, the Geophysical Laboratory, and the Observatories. Income from investments represents approximately 73% and 40% of Carnegie's total revenues for the years ended June 30, 2004 and 2003, respectively. Carnegie's other income is primarily from gifts and federal grants and contracts.

Basis of Accounting and Presentation

The financial statements are prepared on the accrual basis of accounting. Contributions and gifts revenues are classified according to the existence or absence of donor-imposed restrictions. Also, satisfaction of donor-imposed restrictions are reported as releases of restrictions in the statements of activities.

Investments and Cash Equivalents

Carnegie's debt and equity investments are reported at their fair values based on quoted market prices. Carnegie reports investments in limited partnerships at fair value as determined and reported by the general partners. All changes in fair value are recognized in the statements of activities. Carnegie considers all highly liquid debt instruments purchased with remaining maturities of 90 days or less to be cash equivalents. Money market and other highly liquid instruments held by investment managers are reported as investments.

Income Taxes

Carnegie has been recognized by the Internal Revenue Service as exempt from federal income tax under Section 501(c)(3) of the Internal Revenue Code (the Code) except for amounts from unrelated business income. Carnegie is also an educational institution within the meaning of Section 170(b)(1)(A)(ii) of the Code. The Internal Revenue Service has classified Carnegie as other than a private foundation, as defined in Section 509(a) of the Code.

Fair Value of Financial Instruments

Financial instruments of Carnegie include cash equivalents, receivables, investments, bond proceeds held by trustee, accounts and broker payables, and bonds payable. The fair value of investments in debt and equity securities is based on quoted market prices. The fair value of investments in limited partnerships is based on information provided by the general partners.

The fair value of the 1993 Series A bonds payable is based on quoted market prices. The fair value of the 1993 Series B and 2002 revenue bonds payable is estimated to be the carrying value, since these bonds bear adjustable market rates (see note 6).

The fair values of cash equivalents, receivables, bond proceeds held by trustee, and accounts and broker payables approximate their carrying values based on their short maturities.

Use of Estimates

The preparation of financial statements in conformity with accounting principles generally accepted in the United States of America requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and disclosure of contingent assets and liabilities at the date of the financial statements. They also affect the reported amounts of revenues and expenses during the reporting period. Actual results could differ from those estimates.

Property and Equipment

Carnegie capitalizes expenditures for land, buildings and leasehold improvements, telescopes, scientific and administrative equipment, and projects in progress. Routine replacement, maintenance, and repairs are charged to expense.

Depreciation is computed on a straight-line basis, generally over the following estimated useful lives:

Buildings and telescopes – 50 years

Leasehold improvements – lesser of 25 years or the remaining term of the lease

Scientific and administrative equipment – 2-10 years, based on scientific life of equipment

Contributions

Contributions are classified based on the existence or absence of donor-imposed restrictions. Contributions and net assets are classified as follows:

- Unrestricted** – includes all contributions received without donor-imposed restrictions on use or time.
- Temporarily restricted** – includes contributions with donor-imposed restrictions as to purpose of gift and/or time period expended.
- Permanently restricted** – generally includes endowment gifts in which donors stipulated that the corpus be invested in perpetuity. Only the investment income generated from endowments may be spent. Certain endowments require that a portion of the investment income be reinvested in perpetuity.

Contributions to be received after one year are discounted at an appropriate discount rate commensurate with the risks involved. Amortization of the discount is recorded as additional revenue and used in accordance with donor-imposed restrictions, if any.

Gifts of long-lived assets, such as buildings or equipment, are considered unrestricted when placed in service. Cash gifts restricted for investment in long-lived assets are released from restriction when the asset is acquired or as costs are incurred for asset construction.

Grants

Carnegie records revenues on grants from federal agencies only to the extent that reimbursable expenses are incurred. Accordingly, funds received in excess of reimbursable expenses are recorded as deferred revenue, and expenses in excess of reimbursements are recorded as accounts receivable. Reimbursement of indirect costs is based upon provisional rates which are subject to subsequent audit by Carnegie’s federal cognizant agency, the National Science Foundation.

Allocation of Costs

The costs of providing programs and supporting services have been summarized in the statements of

activities. Accordingly, certain costs have been allocated among the programs and supporting services benefited. Fundraising expenses of \$647,977 and \$637,295 for the years ended June 30, 2004 and 2003, respectively, have been included in administrative and general expenses in the accompanying statements of activities.

Reclassification

Certain reclassifications have been made to the 2003 amounts to conform to the 2004 presentation.

(2) Contributions Receivable

Contributions receivable are summarized as follows at June 30, 2004:

Unconditional promises expected to be collected in:	
Less than one year	\$3,712,474
One year to five years	3,848,355
	7,560,829
Less:	
Allowance for uncollectible amounts	(8,500)
Discount to present value	(397,322)
	\$7,155,007

Pledges receivable as of June 30, 2004 and 2003, were discounted using the 3-year U.S. Treasury rate which was approximately 2.7% and 2%, respectively.

(3) Investments

Investments at fair value consisted of the following at June 30, 2004 and 2003:

	2004	2003
Time deposits and money market funds	\$51,168,508	43,208,095
Debt mutual funds	26,596	9,817
Debt securities	86,251,775	105,656,891
Equity securities	150,678,506	156,746,457
Limited real estate partnerships	39,575,148	44,576,914
Limited partnerships	263,069,176	181,825,239
	\$590,769,709	532,023,413

Investment income, net consisted of the following for the years ended June 30, 2004 and 2003:

	2004	2003
Interest and dividends	\$7,487,625	6,103,313
Net realized gains	41,020,315	45,333,103
Net unrealized gains (losses)	39,343,443	(15,693,162)
Less investment management expenses	(1,086,657)	(1,113,895)
	\$86,764,726	34,629,359

As of June 30, 2004, the fair value for approximately \$111.7 million of Carnegie's \$302.6 million of limited real estate partnership and limited partnership investments has been estimated by the general partners in the absence of readily ascertainable values as of that date. As of June 30, 2003, the fair value for approximately \$88.2 million of Carnegie's \$226.4 million of limited real estate partnership and limited partnership investments has been estimated by the general partners in the absence of readily ascertainable values as of that date. However, these estimated fair values may differ from the values that would have been used had a ready market existed.

(4) Property and Equipment

Property and equipment, net consisted of the following at June 30, 2004 and 2003:

	2004	2003
Buildings and improvements	\$53,023,675	45,435,945
Scientific equipment	37,953,848	26,901,472
Telescopes	81,634,844	80,888,440
Construction in progress	14,880,288	17,537,973
Administrative equipment	2,370,705	2,433,184
Land	787,896	787,896
Art	38,105	38,105
	190,689,361	174,023,015
Less accumulated depreciation	(45,876,121)	(40,827,183)
	\$144,813,240	133,195,832

Construction in progress consisted of the following at June 30, 2004 and 2003:

	2004	2003
Buildings	\$12,009,263	4,184,529
Scientific equipment	2,871,025	13,353,444
	\$14,880,288	17,537,973

At June 30, 2004 and 2003, approximately \$84.2 million and \$83.5 million, respectively, of construction in progress and other property, net of accumulated depreciation, was located in Las Campanas, Chile. During construction in 2004 and 2003, Carnegie capitalized interest costs of approximately \$615,000 and \$0, respectively, as construction in progress.

(5) Magellan Consortium

During the year ended June 30, 1998, Carnegie entered into an agreement (Magellan Agreement) with four universities establishing a consortium to build and operate the Magellan telescopes. The two Magellan telescopes are located on Manqui Peak, Las Campanas in Chile. The first telescope, with a cost of approximately \$41,708,000, was placed in service during 2001. The other, with a cost of approximately \$30,148,000, was placed in service in 2003.

The university members of the consortium, by contribution to the construction and operating costs of Magellan, acquire rights of access and oversight as described in the Magellan Agreement. Total contributions by the university members for construction are expected to cover 50% of the total expected costs. As of June 30, 2004, \$36,052,000 has been received. These monies are being used by Carnegie to finance part of the Magellan Telescopes' construction costs. As of June 30, 2004 and 2003, the excess of university members' contributions over operating costs totaled \$32,465,612 and \$32,075,946, respectively, and is included in deferred revenue in the accompanying statements of financial position. The deferred revenue is being recognized ratably as income over the remaining estimated useful lives of the telescopes.

(6) Bonds Payable

1993 California Educational Facilities Authority Revenue Bonds

On November 1, 1993, Carnegie issued \$17.5 million each of Series A and Series B California Educational Facilities Authority Revenue tax-exempt bonds. Bond proceeds were used to finance the Magellan telescope project and the renovation of the facilities of the Observatories at Pasadena. The balances outstanding at June 30, 2004 and 2003, on the Series A issue totaled \$17,500,000 and \$17,494,289, respectively, and on the Series B issue totaled \$17,500,000 and \$17,496,495, respectively. Bond proceeds held by the trustee and unexpended at June 30, 2004 and 2003 totaled \$21 and \$112, respectively.

Series A bonds bear interest at 5.6% payable in arrears semiannually on each April 1 and October 1 and upon maturity on October 1, 2023. Series B bonds bear interest at variable money market rates (ranging from 0.85% to 1.12% during the year, and 1.1% at June 30, 2004) in effect from time to time, up to a maximum of 12% over the applicable money market rate period of between 1 and 270 days and have a stated maturity of October 1, 2023. At the end of each money market rate period, Series B bondholders are required to offer the bonds for repurchase at the applicable money market rate. When repurchased, the Series B bonds are resold at the current applicable money market rate and for a new rate period.

Carnegie is not required to repay the Series A and B bonds until the October 1, 2023, maturity date. Sinking fund redemptions begin in 2019 in installments for both series. The fair value of Series A bonds payable at June 30, 2004 and 2003, based on quoted market prices is estimated at \$19,069,000 and \$20,051,000, respectively. The fair value of Series B bonds payable at June 30, 2004 and 2003 is estimated to approximate carrying value as the mandatory tender dates on which the bonds are repriced are generally within three months of year end.

2002 Maryland Health and Higher Education Facilities Authority Revenue Bond

On October 23, 2002, the Maryland Health and Higher Education Facilities Authority (MHHEFA) issued \$30 million of its Revenue Bonds on behalf of Carnegie. Bond proceeds are being used to construct and equip a new facility for Carnegie's Department of Embryology on the Johns Hopkins Homewood Campus in Baltimore, Maryland. Construction began in April 2003, and the facility is expected to be ready for occupancy in March 2005.

The balance outstanding at June 30, 2004 and 2003 on the Carnegie 2002 Series totaled \$29,670,359 and \$29,724,888, respectively. The balance outstanding is net of unamortized bond issue costs. Bond proceeds held by the trustee and unexpended at June 30, 2004 totaled \$18,209,170.

The bonds were issued in the weekly mode and bear interest at a variable rate determined by the remarketing agent, Lehman Brothers. The rates fluctuated between 0.68% and 1.25% during the year ended June 30, 2004 (see note 7). The rate at June 30, 2004 was 1.03%. Rates on remarketed bonds are selected in such a manner that the selling price will closely approximate the face value, but under no circumstances will the rate exceed 12% per annum. Interest is payable on the first business day of each month. Bonds in the weekly mode are subject to redemption at the request of Carnegie on any interest payment date. Bonds in weekly mode can be changed to daily, commercial paper, term rate or fixed rate mode at the request of Carnegie. Bonds are subject to mandatory tender for purchase prior to any change in the interest rate mode.

Scheduled maturities and sinking fund requirements are as follows:

Due:	
October 1, 2033	\$6,000,000
October 1, 2034	6,000,000
October 1, 2035	6,000,000
October 1, 2036	6,000,000
October 1, 2037	6,000,000
	\$30,000,000

Standby credit facilities have been established with SunTrust Bank in the aggregate amount of \$30,000,000 as of June 30, 2003, expiring January 31, 2006. Carnegie pays 0.08% per annum on the amount of the available commitment, payable quarterly in arrears. SunTrust Bank may extend the agreement, but Carnegie is not required to maintain a liquidity facility for any bonds. The standby credit facility has not been used as of June 30, 2004.

(7) Interest Rate Swap Agreement

Carnegie entered into a swap agreement with an effective date of October 23, 2002. This swap agreement relates to \$15 million face amount of its Series 2002 Maryland Health and Higher Education Facilities Authority Revenue Bonds (see note 6). The agreement provides for Lehman Brothers Special Financing Inc. to receive 3.717% in interest on a notional amount of \$15 million and to pay interest at a floating rate of 68% of the three-month LIBOR rate, reducing on the dates and in the amounts as follows:

October 1, 2033	\$3,000,000
October 1, 2034	3,000,000
October 1, 2035	3,000,000
October 1, 2036	3,000,000

The interest rate swap agreement was entered into by Carnegie to mitigate the risk of changes in interest rates associated with variable interest rate indebtedness. Carnegie applies the provisions of FASB Statement No. 133, *Accounting for Derivative Instruments and Hedging Activities*. This standard requires certain derivative financial instruments to be recorded at fair value. The interest rate swap agreement described above is a derivative instrument that is required to be recorded at fair value. For 2004, this was valued as an asset of \$174,107 and included in accounts receivable on the accompanying statements of financial position. For 2003, this was valued as a liability of \$1,246,619 and included in accounts payable and accrued expenses on the accompanying statements of financial position. The change in fair value for the years ended June 30, 2004 and 2003, was a gain of \$1,420,726 and a loss of \$1,246,619, respectively, and is included as a change in other income.

(8) Employee Benefit Plans

Retirement Plan

Carnegie has a noncontributory, defined contribution, money-purchase retirement plan in which all U.S. personnel are eligible to participate. After one year of participation, an individual's benefits are fully vested. The Plan has been funded through individually owned annuities issued by Teachers' Insurance and Annuity Association (TIAA) and College Retirement Equities Fund (CREF). Contributions made by Carnegie totaled approximately \$2,990,000 and \$2,783,000 for the years ended June 30, 2004 and 2003, respectively.

Postretirement Benefits Plan

Carnegie provides postretirement medical benefits to all employees who retire after age 55 and have at least 10 years of service. Cash payments made by Carnegie for these benefits totaled approximately \$532,000 and \$587,000 for the years ended June 30, 2004 and 2003, respectively.

The expense for postretirement benefits for the years ended June 30, 2004 and 2003 consists of the following:

	2004	2003
Service cost – benefits		
earned during the year	\$1,233,000	576,000
Interest cost on projected		
benefit obligation	1,214,000	734,000
Amortization of gain	396,000	—
Postretirement		
benefit cost	\$2,843,000	1,310,000

The 2004 postretirement benefits expense was approximately \$2,311,000 more than the cash expense of \$532,000, and the 2003 postretirement benefits expense was approximately \$723,000 more than the cash expense of \$587,000. The postretirement benefits expense was allocated among program and supporting services expenses in the accompanying statements of activities.

The reconciliation of the Plan’s funded status to amounts recognized in the financial statements at June 30, 2004 and 2003 follows:

	2004	2003
Change in benefit obligation:		
Benefit obligation at		
beginning of year	\$20,531,000	10,300,000
Service cost	1,233,000	576,000
Interest cost	1,214,000	734,000
Actuarial loss	(3,246,000)	9,508,000
Benefits paid	(532,000)	(587,000)
Benefit obligation at		
end of year	19,200,000	20,531,000
Change in plan assets:		
Fair value of plan assets		
at beginning of year	—	—
Contribution to plan	532,000	587,000
Benefits paid	(532,000)	(587,000)
Fair value of plan assets		
at end of year	—	—
Funded status	(19,200,000)	(20,531,000)
Unrecognized net		
actuarial loss	5,530,000	9,172,000
Accrued benefit cost	\$(13,670,000)	(11,359,000)

The present value of the benefit obligation as of June 30, 2004, was determined using an assumed discount rate of 6.25%. The present value of the benefit obligation as of June 30, 2003, was determined using an assumed discount rate of 6%. Carnegie’s policy is to fund postretirement benefits as claims and administrative fees are paid.

For measurement purposes, an 11.5% annual rate of increase in the per capita cost of pre-Medicare covered healthcare benefits and a 13% annual rate of increase in the per capita cost of post-Medicare covered healthcare benefits was assumed for 2004; the rate for both types of benefits was assumed to decrease gradually to 5.5% in 2016 and remain at that level thereafter. The healthcare cost trend rate assumption has a significant effect on the amounts reported. An one-percentage point change in assumed annual healthcare cost trend rate would have the following effects:

The measurement date used to determine postretirement benefit obligations is July 1.

	One-percentage point increase	One-percentage point decrease
Effect on total of		
service and interest		
cost components	\$627,000	(469,000)
Effect on		
postretirement		
benefit obligation	2,792,000	(3,193,000)

Carnegie expects to contribute approximately \$506,000 to its postretirement benefit plan during the year ended June 30, 2005.

The following benefit payments (net of retiree contributions), which reflect expected future service, are expected to be paid, as of June 30, 2004:

2005	\$506,000
2006	570,000
2007	641,000
2008	741,000
2009	832,000
2010 – 2014	5,562,000
	\$8,852,000

On December 8, 2003, the President signed into law the Medicare Prescription Drug Improvement and Modernization Act of 2003 (the Act). The Act introduces prescription drug benefits under Medicare (Medicare Part D) as well as a federal subsidy to sponsors of retiree health care benefit plans that provide a benefit that is at least actuarially equivalent to Medicare Part D. FASB Statement 106, *Employers' Accounting for Postretirement Benefits Other Than Pensions* (SFAS 106), requires presently enacted changes in relevant laws to be considered in current period measurements of postretirement costs and the accumulated postretirement benefit obligation. However, certain accounting issues raised by the Act are not specifically addressed by SFAS 106, and significant uncertainties exist as to the direct and indirect effects of the Act.

In January 2004, the Financial Accounting Standards Board issued SFAS 106-1, *Accounting and Disclosure Requirements Related to the Medicare Prescription Drug, Improvement and Modernization Act of 2003*. SFAS No. 106-1, which became effective for fiscal years ending after December 7, 2003, allows for a deferral in recognizing the effects of the Act until authoritative guidance on the accounting for the federal subsidy is issued or other events occur. For the year end June 30, 2004, Carnegie has elected deferral, as management and its advisors do not have sufficient information available on which to measure the effects of the Act on Carnegie's postretirement benefit costs and obligation.

(9) Net Assets

Temporarily Restricted Net Assets

Temporarily restricted net assets were available to support the following donor-restricted purposes at June 30, 2004 and 2003:

	2004	2003
Specific research programs	\$21,862,442	14,384,361
Equipment acquisition and construction	2,839,318	3,638,444
Passage of time	2,208,243	6,185,145
	\$26,910,003	24,207,950

Permanently Restricted Net Assets

Permanently restricted net assets consisted of permanent endowments, the income from which is available to support the following donor-restricted purposes at June 30, 2004 and 2003:

	2004	2003
Specific research programs	\$14,546,237	15,716,041
Equipment acquisition and construction	2,704,719	1,204,719
General support (Carnegie endowment)	22,000,000	22,000,000
	\$39,250,956	38,920,760

Net Assets Released from Restrictions and Matching of Endowment

During 2004 and 2003, Carnegie met donor-imposed requirements on certain gifts and, therefore, released temporarily restricted net assets as follows:

	2004	2003
Specific research programs	\$3,686,708	2,984,309
Equipment acquisition and construction	4,114,912	962,034
General support (Carnegie endowment)	1,847,571	2,375,241
	\$9,649,191	6,321,584

During 2004, Carnegie allocated \$223,500 of unrestricted net assets to establish a Plant Biology endowment fund to match a donor's contribution. This amount is included as specific research programs in permanently restricted net assets.

(10) Commitments

Carnegie entered into a contract with the University of Arizona for the construction of a secondary mirror and support system for the second telescope in the Magellan project. The amount of the contract is approximately \$590,000, none of which had been incurred at June 30, 2004. Carnegie also has other contracts for projects at the Observatories amounting to \$1,107,000 as of June 30, 2004.

Carnegie has outstanding commitments to invest approximately \$86.5 million in limited partnerships at June 30, 2004.

(11) Lease Arrangements

Carnegie leases a portion of the land it owns in Las Campanas, Chile, to other organizations. These organizations have built and operate telescopes on the land. Most of the lease arrangements are not specific and some are at no cost to the other organizations. One of the lease arrangements is non-cancelable and had annual rent of approximately \$160,000 for each of the fiscal years 2004 and 2003. For the no-cost leases, the value of the leases could not be determined and is not considered significant and, accordingly, contributions have not been recorded in the financial statements.

Carnegie also leases a portion of one of its laboratories to another organization for an indefinite term. Rents to be received under the agreement are approximately \$536,000 annually, adjusted for CPI increases. Beginning in April 2005, rents will increase approximately 40% when the laboratory moves to a larger space.

Carnegie leases land and buildings. The monetary terms of the leases are considerably below fair value; however, these terms were developed considering other nonmonetary transactions between Carnegie and the lessors. The substance of the transactions indicates arms-length terms between Carnegie and the lessors. The monetary value of the leases could not be determined and has not been recorded in the financial statements.

(12) Contingencies

Costs charged to the federal government under cost-reimbursement grants and contracts are subject to government audit. Therefore, all such costs are subject to adjustment. Management believes that adjustments, if any, would not have a significant effect on the financial statements.

(13) Related-Party Transactions

Carnegie recorded contributions from its trustees, officers and directors of \$4,655,832 and \$21,440,335, for the years ended June 30, 2004 and 2003, respectively.

(14) Risks and Uncertainties

Carnegie's invested assets consist of common stocks, fixed income securities and other investment securities. Investment securities are exposed to various risks, such as interest rate, market and credit. Due to the level of uncertainty related to changes in interest rates, market volatility and credit risks, it is at least reasonably possible that changes in these risks could materially affect the fair value of investments reported in the statement of financial position as of June 30, 2004 and 2003. However, the diversification of Carnegie's invested assets among these various asset classes should mitigate the impact of any dramatic change on any one asset class.

Schedule of Expenses

Years ended June 30, 2004 and 2003

	2004			2003		
	Carnegie funds	Federal and private grants	Total expenses	Carnegie funds	Federal and private grants	Total expenses
Personnel costs:						
Salaries	\$14,475,943	4,780,166	19,256,109	13,641,577	4,636,962	18,278,539
Fringe benefits and payroll taxes	10,009,374	2,238,258	12,247,632	7,461,155	2,200,589	9,661,744
Total personnel costs	24,485,317	7,018,424	31,503,741	21,102,732	6,837,551	27,940,283
Fellowship grants and awards	1,966,003	948,967	2,914,970	1,674,086	648,011	2,322,097
Depreciation	7,794,105	—	7,794,105	6,009,836	—	6,009,836
General expenses:						
Educational and research supplies	2,438,265	5,232,412	7,670,677	2,161,910	5,565,549	7,727,459
Building maintenance and operation	8,409,920	117,067	8,526,987	2,716,592	693,621	3,410,213
Travel and meetings	1,021,637	746,156	1,767,793	1,250,038	680,267	1,930,305
Publications	40,854	31,977	72,831	40,842	39,231	80,073
Shop	99,989	23,649	123,638	63,573	—	63,573
Telephone	201,400	5,631	207,031	187,470	10,363	197,833
Books and subscriptions	342,961	—	342,961	310,759	—	310,759
Administrative and general	1,299,174	186,264	1,485,438	1,393,813	186,887	1,580,700
Facilities construction	8,530,528	—	8,530,528	1,710,375	—	1,710,375
Interest	1,771,130	—	1,771,130	1,364,369	—	1,364,369
Printing and copying	77,751	—	77,751	80,780	—	80,780
Shipping and postage	169,309	24,681	193,990	161,121	27,582	188,703
Insurance, taxes, and professional fees	2,759,936	72,450	2,832,386	2,080,254	130,192	2,210,446
Equipment	1,724,656	1,673,942	3,398,598	2,485,875	3,390,935	5,876,810
Fundraising expense	647,977	—	647,977	637,295	—	637,295
Total general expenses	29,535,487	8,114,229	37,649,716	16,645,066	10,724,627	27,369,693
Total direct costs	63,780,912	16,081,620	79,862,532	45,431,720	18,210,189	63,641,909
Indirect costs:						
Grants and contracts	(6,376,746)	6,376,746	—	(6,495,399)	6,495,399	—
Total costs	57,404,166	22,458,366	79,862,532	38,936,321	24,705,588	63,641,909
Capitalized scientific equipment and facilities	(17,424,577)	(1,471,930)	(18,896,507)	(5,871,899)	(3,338,928)	(9,210,827)
Total expenses	\$39,979,589	20,986,436	60,966,025	33,064,422	21,366,660	54,431,082

See accompanying independent auditors' report.

